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THESIS

**ANALYSIS OF EFFECTIVENESS OF CEC
(COOPERATIVE ENGAGEMENT CAPABILITY) USING
SCHUTZER'S C^2 THEORY**

by

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December 2003

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CAPABILITY) USING SCHUTZER'S C^2 THEORY**

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ABSTRACT

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EXECUTIVE SUMMARY

Information superiority can be obtained by enhancement of the command and control system. While weapon systems may have been developed to a point of decreasing returns regarding firepower, command and control (C^2) systems can be developed further. The force that has superior C^2 may win the fight in the future by information superiority.

Currently, there is no appropriate methodology to assess the contribution from the C^2 system to improved combat outcomes. This thesis develops a methodology to address Cooperative Engagement Capability (CEC) by modifying C^2 theory developed by D.M. Schutzer. [Schutzer, 1982] I address the time line that Schutzer suggested as the key to addressing C^2 improvements concretely and modify the MOE he designed. Based on this modified MOE, developed through simulation analysis of an air defense scenario, I quantify the improvement in command and control systems by the CEC system.

This thesis introduces an anti-air defense scenario. There are two forces, a red force that attacks with anti-ship cruise missiles and blue force that defends with anti-air missiles. This scenario is modeled in a spreadsheet simulation, and explores modified C^2 theory with CEC system, based on Schutzer research and my enhancements. This simulation allows for a comparison of CEC versus Network Centric Warfare (NCW) and Platform Centric Warfare (PCW) at the same time. This analysis provides insights into any improvement and helps determine the effectiveness of CEC system.

In estimating the C^2 MOE mathematically, I define three parameters (decision time, information certainty, and human factor) and estimate their values and I calculate three factors (probability of survival, allocation ratio, and exchange rate). Information certainty and human factor are my contributions to C^2 analysis. Information certainty of NCW and CEC is affected directly by the number of ships, but under PCW, information certainty stays constant. This implies the contribution of the network complexity to C^2 system. The human factor implies commander's personal character. I assume that NCW is affected by both of these parameters, but that CEC is not affected by human factor.

I calculate the decision time for each C^2 operating process and implement into MOE equation. The result shows that CEC can improve the friendly force chance for success relative to NCW and PCW. Superior information certainty greatly affects the MOE.

I estimate the enhanced coefficient α of the probability of survival based on a simulation model. I simulate an air defense scenario and use the input I derived explaining decision time, information certainty, and human factor as simulation parameters. In addition, I introduce missile inter arrival time into simulation. My simulation output indicates that PCW cannot be compared with NCW or CEC, in that PCW has no survivability within simulation environment. In order to estimate α and compare NCW and CEC, I develop a metamodel through polynomial regression based on simulation outputs. This metamodel show NCW and CEC are not affected by human factor but are affected by missile inter arrival time and information certainty. Both metamodels provide prediction capability by mapping a response surface.

Based on the regression equations, I obtain 100 response surface points for each NCW and CEC, and calculate α with these data points. With a simple statistical calculation, I estimate mean value and variance of α of CEC to NCW. The mean value is 1.299 and variance is 0.00476, as the variance very small in relation to mean, I conclude with confidence that CEC can improve MOE by 1.299 relative to NCW.

As a result, I find the NCW or CEC can improve capability of C^2 system, with CEC providing the greatest improvement. Statistical analysis shows that NCW and CEC are not affected by human factor. Enhancement of C^2 system results from the information certainty that is caused by network reinforcement. Finally, this research supports the CEC methodology and its contribution to engagement capability.

I. INTRODUCTION

A. BACKGROUND AND PURPOSE OF RESEARCH

Operations in the littoral theater have become the principal Navy scenario. In particular, the threat of enemy cruise or ballistic missile and supersonic aircraft emerged as the most critical and dangerous. Currently, the U.S. Navy is developing the Cooperative Engagement Capability (CEC) with Johns Hopkins Applied Physical Laboratory (APL). CEC allows for information superiority by enabling combat systems to share unfiltered sensor measurement data associated with tracks with rapid timing and precision to enable the disparate battle group units to operate as one. [Johns Hopkins, 1995]

Information superiority can be obtained by enhancement of the command and control system. While weapon systems may have been developed to a point of decreasing returns regarding firepower, command and control (C^2) systems can be developed further. The force that has superior C^2 may win the fight in the future by information superiority.

Currently, there is no appropriate methodology to assess the contribution from the C^2 system to improved combat outcomes. This thesis develops a methodology to address CEC by modifying C^2 theory developed by D.M. Schutzer. [Schutzer, 1982] I address the time line that Schutzer suggested as the key to addressing C^2 improvements concretely and modify the MOE he designed. Based on this modified MOE, developed through simulation analysis of an air defense scenario, I quantify the improvement in command and control systems by the CEC system.

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B. SCOPE OF RESEARCH

I introduce a new model by modification to existing C^2 theory with addition of the CEC system. D. M. Schutzer's C^2 theory, though published over 20 years ago, reflects the effectiveness of advanced command and control system that approximates today's interpretation of CEC.

This research reviews Schutzer's description and representation of three factors of his C^2 MOE, which are the probability of survival, the allocation ratio, and the exchange rate. After an overview of the Navy's proposed CEC system, I discuss how CEC is developed for air defense, to include CEC's concept, special character, superiority and implication for C^2 theory. The analysis focuses on the amount of decision time available for CEC system, and leads to conclusions regarding NCW and PCW, and their differences.

Chapter III introduces the new analytical model with the concepts described in Chapter II. After describing MOE factors of C^2 theory in detail, this study generates a modified new MOE model, modifies the probability of survival, allocation ratio, and exchange rate in C^2 theory by considering the decision time changed by CEC, NCW and PCW operating systems. Finally, I will suggest a new model that can evaluate modern information warfare.

In Chapter IV, the research focuses on a simulation model of anti missile defense during surface engagement between two forces. Red force attacks with anti-ship cruise missiles. My analysis measures the effectiveness of C^2 system with modified MOE factors by CEC and NCW systems. I compare the results, noting how much the effectiveness of C^2 system is increased after constructing CEC system and comparing to NCW system. Chapter V concludes this research with discussion of the implication of measuring effectiveness for developing a new information warfare system.

C. SCHUTZER'S C^2 THEORY

D. M. Schutzer proposed an MOE for his model of naval engagement that represents a measure of the contribution of improved C^2 . This MOE compares the initial force size with the number of remaining forces after engagement in a certain time interval t and where each unit of force has its own special quantifiable values. [Schutzer, 1982]

Of great interest to this research is the MOE's inclusion of the probability of survival, allocation ratio and exchange rate. An engagement between blue and red force causes damage by each opponent's value with a specific ratio. Schutzer states that the number of remaining forces can be calculated as a function of the number of enemy force and the duration time of engagement. The MOE is calculated by comparing the ratio of initial value of force with remaining value of force after engagement. With this concept, Schutzer suggests that the MOE model measure the synergism of fighting power through Lanchester's square law. The MOE is below.

$$MOE_j = \frac{< N_j^2 > - < M_j^2 >}{N_0^2} \quad (1-1)$$

Where, $< N_j^2 >$ = the value of blue remaining force after j^{th} engagement

$< M_j^2 >$ = the value of red remaining force after j^{th} engagement

$< N_0^2 >$ = the value of initial total of blue and red forces in the specific j^{th} engagement

The elements of the MOE equation are shown below.

$$< N_j^2 > = \sum_{k=1}^T \sum_{k'=1}^S \frac{P_{kj} a_{kj} n_{kj}^2}{1 + X_{kk'}} \quad (1-2)$$

$$< M_j^2 > = \sum_{k=1}^T \sum_{k'=1}^S \frac{X_{kk'} q_{k'j} b_{k'j} m_{k'j}^2}{1 + X_{kk'}} \quad (1-3)$$

$$< N_0^2 > = \sum_{k=1}^T \sum_{k'=1}^S n_{kj}^2 \quad (1-4)$$

Where, k = the number of unit in each type of blue force

k' = the number of unit in each type of red force

P_{kj} = the probability of survival in j^{th} engagement

a_{kj} = the allocation ratio of each types of blue force in j^{th} engagement

$X_{kk'}$ = the exchange rate of k unit blue force to k' unit of red force which means the loss of blue force to the loss of red force during engagement

$q_{k'j}$ = the probability of survival of red force

b_{kj} = the allocation ratio of red force

n_{kj} = the number of unit blue force in j^{th} engagement

m_{kj} = the number of unit red force in j^{th} engagement

Based on this MOE, the effectiveness in C^2 systems is influenced by these three elementary equations (1-2, 1-3, 1-4). In turns, equations 1-2 and 1-3 are influenced by three factors, the probability of survival, allocation ratio and exchange rate. This relation is shown below.

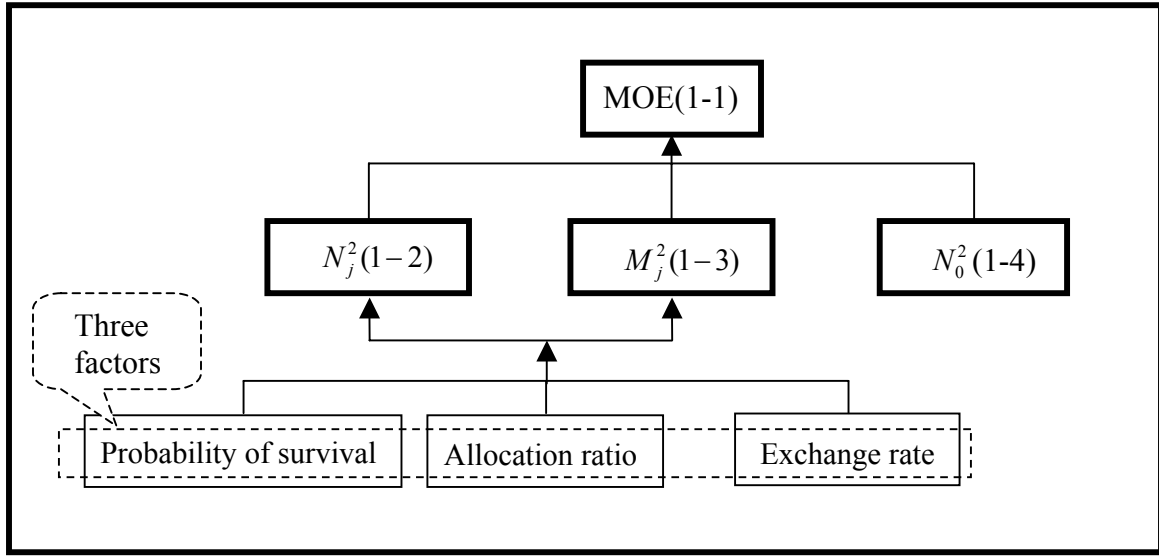


Figure 1. Hierarchy of MOE.

Schutzer suggested MOE model and its ability to access as enhanced C^2 system is very conceptual and abstract. He used time impact on three factors without detailed analysis. Each of these factors and their time impact are therefore examined in detail in Chapter III. I incorporate a more detailed description of the input factors that Schutzer includes in his equation for the probability of survival. I then use a simulation to examine the effects of varying these factors. The result is a model that can predict the impact of CEC (when compared to PCW and NCW) on an engagement. This result is, of course, very scenario dependent.

II. OVERVIEW OF CEC

A. CONCEPT OF CEC SYSTEM

1. Introduction

Operation in the littoral theater includes complexity never considered in the Cold War era. For theater air defense, the complexities include natural environment and its effects on sensor range and reduction in the time available for defense system to react. In addition, commercial, nonbelligerent aircraft and ships compound the already difficult problem of sorting friends, neutrals, and hostiles during major Allied operation involving many other ships and aircraft.

To successfully perform its intended missions the Navy may need to defend itself and its assets ashore with combatants dispersed over thousand of square miles. Each combatant will possess one or several sensors totaling, perhaps, more than 50 among Allied threat forces, and each sensor will observe a somewhat different view of the situation because of its unique characteristic and vantage point. Amidst this disparity in knowledge among coordinating units are efforts to correlate target tracks and identification data via conventional command and control system and to coordinate 20 to 30 missile launchers and a comparable number of interceptor aircraft.

Coalescing this collection of equipment into a single war-fighting entity requires a system that will combine both new-generation and old air defense systems by sharing sensor, decision, and engagement data among combatant units, without compromising timeliness, volume, and accuracy of data. The system must create an identical picture at each unit of sufficient quality to be treated as local data for engagements, even though the data may have arrived from 30 to 40 miles away. If a common, detailed database is available to provide a shared air picture as well as the ability to engage targets that may not be seen locally, a new level of capability may be attained. [Johns Hopkins, 1995]

This ability is precisely what the Cooperative Engagement Capability (CEC) provides for a network of combatants. Recent tests demonstrated that from older, short-range systems such as NATO Sea Sparrow through the latest Aegis baseline, CEC can provide greater defense capabilities and even provide new types of capabilities to a battle

force. However, CEC does not obviate the need for advance in sensors, fire control, and interceptors. Rather, CEC allows the benefits of the newest system to be shared with older units and provides for greater total capability despite the decline in the number of U.S. and Allied forces. [Johns Hopkins, 1995]

2. CEC Description

CEC is based on the approach of taking full advantage of the diversity provided by each combatant at a different location with different sensor and weapons frequencies and features. This approach requires sharing measurements from every sensor (unfiltered range, bearing, elevation, and, if available, Doppler updates) among all units while retaining the critical data characteristics of accuracy and timeliness. For effective use, the data must be integrated into each unit's combat system so that it can use the data as if it were generated onboard that unit. Thus, the battle force of units networked in this way can operate as a single, distributed, theater defensive system. A focus of the current study is comparing the important principle of operation to network centric warfare, which merely shares the operational picture and not target-quality tracking data. [Johns Hopkins, 1995]

a. Composite Tracking

CEC can share radar measurement data that are independently processed at each unit into composite tracks with input data appropriately weighted by the measurement accuracy of each sensor input. Thus, if any unit's onboard radar fails to receive updates for a time, the track does not simply coast (risking loss or de-correlation from the tracks of other units reported over tactical command and control data links), but rather it continues because of data availability from other units. This function is performed for radar and identification Friend or Foe (IFF) system with IFF transponder responses as "measurement" inputs to the composite track in process. The composite track function is accompanied by automatic CEC track number commonality, even when tracking is being performed simultaneously at each unit. Also provided is the composite identification doctrine, as input from a console of a selected net control unit (NCU), for all CEC units to implement to jointly decide on a target's classification. [Johns Hopkins, 1995]

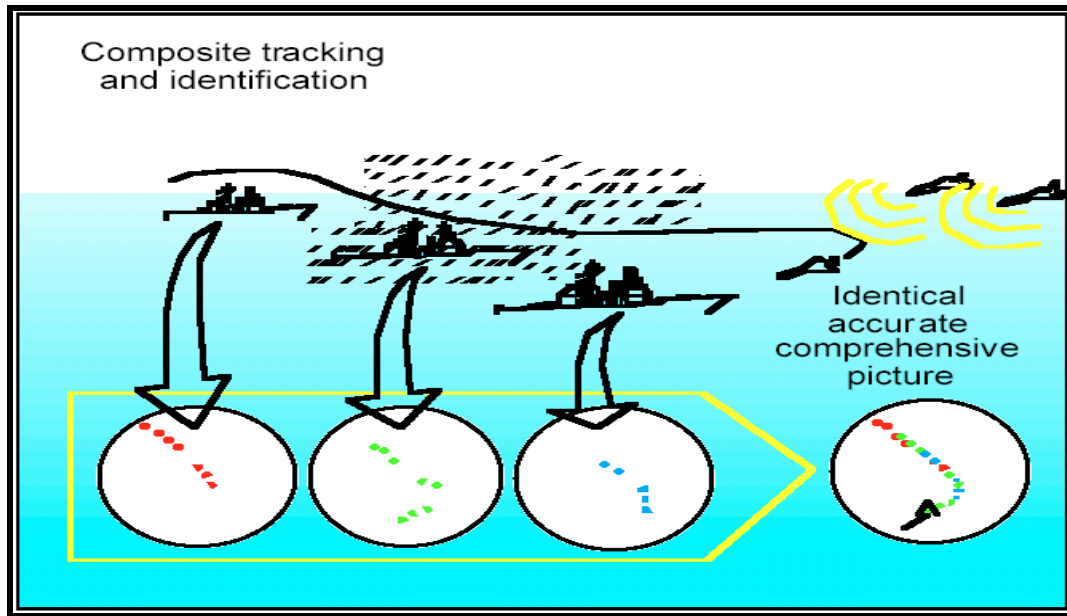


Figure 2. Composite Tracking and Identification [From Johns Hopkins, 1995].

b. Precision Cueing

To facilitate maximum sensor coverage on any track, a means of special acquisition cueing is available. If a CEC track is formed from remote data but a unit does not locally hold the with its radars, the combat system can automatically initiate action (a cue) to attempt the start of a local track if the track meets that unit's threat criteria. A CEC cue allows one or several radar dwells (with number and pattern determined by accuracy of the sensor(s) holding the target). Given that at least one radar with fire control accuracy in the network contributes to the composite track of target, then cued acquisition by a phased array radar with only a single radar dwell at high power and maximum sensitivity is possible, even if substantial target maneuvering occurs during target acquisition. For rotating radar, the target may be acquired by a localized sensitivity increase in a single sweep rather than by requiring several radar rotations to transition to track. Studies and tests have showed that the local acquisition range can be greatly extended simply by not requiring the usual transition-to-track thresholds (for detection and false alarm probability control) to be required since the precise target location is known. Retention of radar accuracy within the CEC net is accomplished via a precision sensor-alignment "gridlock" process using the local and remote sensor measurement. [Johns Hopkins, 1995]

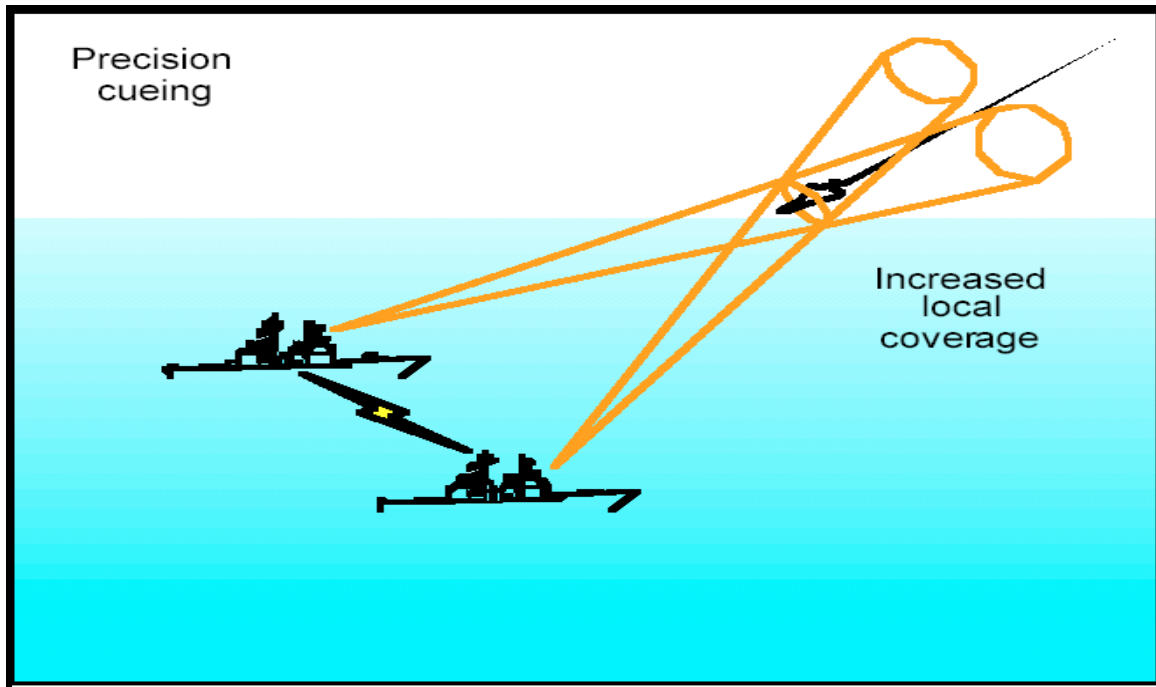


Figure 3. Precision Cueing [From Johns Hopkins, 1995].

c. Coordinated, Cooperative Engagement

With the combination of precision gridlock, very low time delay, and very high update rate, a combatant may fire a missile and guide it to intercept a target, even a maneuvering one, using radar data from another CEC unit even if it never acquires the target with its own radars. This capability is known as engagement on remote data, and, with the Navy's Standard Missile-2 (SM-2) series, allows midcourse guidance and pointing of the terminal homing illuminator using off board data. The remote engagement operation is essentially transparent to the combat system operators. Engagement can be coordinated, whether conventional or cooperative, via real-time knowledge of the detailed status of every missile engagement within the CEC network. Moreover, a coordination doctrine may be activated by the designated NCU for automated engagement recommendations at each unit based on force-level engagement calculation. [Johns Hopkins, 1995]

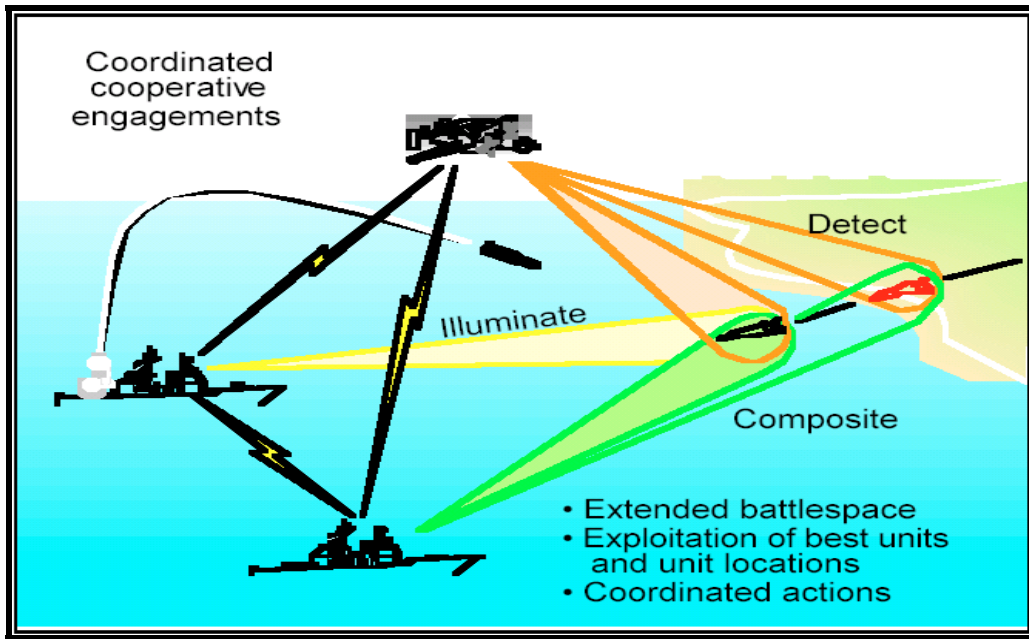


Figure 4. Coordinated, Cooperative Engagement [From Johns Hopkins, 1995].

B. SUMMARY

The CEC was developed in response to the need to maintain and extend Fleet air defense against advanced, next-generation threats as well as to complement advances in sensor and weapon systems. By networking at the measurement level, each unit can view the theater air situation through the collective sensors of the combatants, and units are no longer limited in knowledge of air targets and in missile intercept range by the performance limits of their own sensors. The result is a quantum improvement in which advance threats may be composite-tracked and engaged using remote data by networked units that would otherwise not have been able to track or engage them. In a 1994 *U.S. News & World Report* article, Rear Admiral Philip Coady, Jr., Director of Navy surface Warfare, observed about CEC that “the composite picture is more than the sum of the parts.” In providing the improvement in air defense performance, CEC has been recognized by Congress, DoD, and the Navy as dissipating the “fog of battle” by virtue of composite tracking and identification with high accuracy and fidelity resulting in an identical database at each networked unit. A new generation of precision coordination and tactics has thus been made possible, as recognized by the *USS Eisenhower* battle group command and staff. Further, substantial theater-wide air defense and coordination enhancements are possible in the joint arena by CEC integration into U.S. and Allied Air

Force, Army, and Marine Corps sensors and air defense systems. This potential has led to congressional and DoD direction that the services explore joint CEC introduction. The CEC is the only system of its kind and is widely considered as the start of a new era in war fighting in which precise knowledge is available to theater forces, enabling highly cooperative operations against technologically advanced and diverse threats. [Johns Hopkins, 1995]

III. MODEL DEVELOPMENT

A. SCHUTZER'S THREE FACTORS OF MOE IN C^2 THEORY

Schutzer describes three factors that impact the MOE in C^2 theory. These factors are probability of survival, allocation ratio and exchange rate. I modify these equations later in this chapter, based on both a simple analytical model as well as simulation.

An essential component of Schutzer's theory is his detailed discussion of the steps in the search and engagement process and the times associated with these steps. In the figure below, it is clear that Schutzer focuses on 4 major processes (sense, process, compare, and decide). These four processes are divided further on right side (event occurs, event detected, etc). These right side events are defined in terms of time and are assigned the variable t with an appropriate subscript. The equations discussed throughout this chapter refer to the variables noted in the figure. Essentially, it was Schutzer's primary conclusion that improved C^2 could reduce the time necessary to complete one or more of these events.

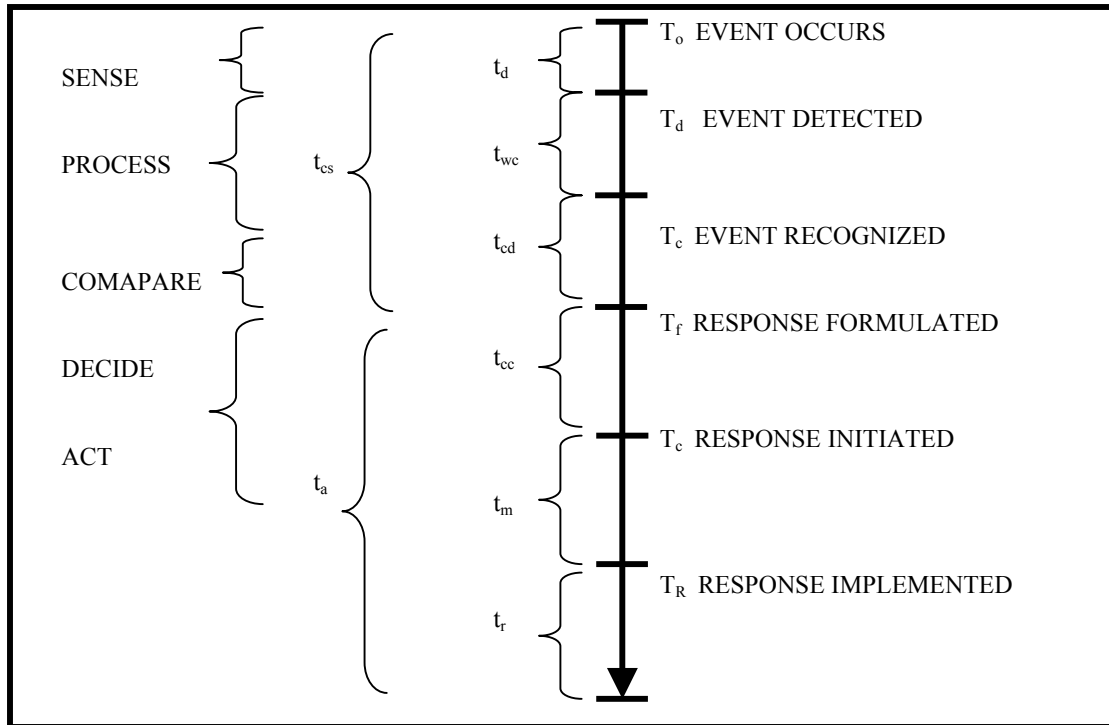


Figure 5. Time Impact Line [From Schutzer, 1982].

1. The Probability of Survival

The probability of survival is directly related to the probability of how fast and successfully a ship reacts to incoming enemy threat or attack in order to have sufficient time to defend themselves and other forces. In Schutzer's C^2 theory, the probability of survival is based on the ability to recognize and analyze enemy disposition. This means that the probability of survival increased by minimizing uncertainty about enemy disposition on the zone in battle where the commander is interested. The equation of probability of survival is as follows.

Assume that the enemy units distribute randomly in the interested zone and density of enemy distribution is $\rho = \frac{A}{N}$, where, N is the number of force, and A is area of interested zone. If the uncertainty in this zone is ΔA , the area of a sensor's coverage, $N = \rho \Delta A$ (which refers to blue force), the equation about accuracy of information is

$$\text{(Probability of correct information)} \quad P = \frac{1}{1 + \rho \Delta A} \quad (3-1)$$

The probability of accuracy about enemy force decreases as uncertainty ΔA increases. ΔA is composed of four combat elements. These are V_p (enemy movement toward the friend force), σ^2 (initial accuracy of information), t_{cs} (command and control time) and ρ (density of enemy unit that can be threat to friend force's survival) and these can influence the accuracy of information. That is $\Delta A = C_1 V_p t_{cs}^2 \sigma^2$. Apply this equation into equation into 3-1 yields

$$P_c = \frac{1}{1 + C_1 \rho V_p t_{cs}^2 \sigma^2} \quad (3-2)$$

Schutzer postulated that this probability of correct information is directly linked to probability of survival of a ship. In fact, he stated that $P(\text{survival})$

$$\alpha P_{kj} = \frac{1}{1 + C_1 [V_p \sigma^2 t_{cs}^2]} \quad (3-3)$$

Where, C_1 = Arbitrary constant

α = Coefficient of the probability of survival

V_p = Speed of platform

σ^2 = Initial information accuracy

He also stated that the more the C^2 system is reinforced, the more the effectiveness of combat element increases. Then as the probability of gaining information about the enemy increases, the probability of survival also increases. Thus, the probability of survival after reinforcement in command and control system is improved by a factor designed as α , such that probability of survival is now αP_{kj} . [Paek, 2002]

P (probability of survival before reinforcement in C^2 system) < αP (probability of survival after reinforcement in C^2 system), here $\alpha > 1$

2. The Allocation Ratio

The allocation ratio is that ratio of assets put into specific engagement. It is represented by the ratio of friendly assets relative to the area of battlefield that the commander can control. The maximum input ratio is 1 before reinforcement. The C^2 system is reinforced in the battlefield zone where command and control may be expanded. The results are that the force could be able to achieve superiority in searching, detection, and decision-making. It equates to increase effectiveness of assets. The force can obtain the same result with smaller units after reinforcement in the C^2 system.

The allocation ratio of force unit is a function of controllable range (r_c). The controllable range is a function of maximum weapon firing range, speed of platform, and the difference between available time and maximum weapon flight time. The equation is as below,

$$r_c = r_w + V_p(t_a - t_w) \quad (3-4)$$

Where, r_c = Controllable range

r_w = Maximum weapon firing range

V_p = Speed of platform

t_a = Available time of unit force

t_w = Maximum weapon flight time

In equation 3-4, the maximum weapon firing range and maximum weapon flight time are constant, so available time of unit force (t_a) is the main factor in deciding controllable range. The more time a force unit has, the larger its controllable range.

Schutzer revised the above equation to reflect the ratio of previous controllable range divided with maximum weapon firing range.

$$\frac{r_c}{r_w} = 1 + \frac{V_p (t_a - t_w)}{r_w} \quad (3-5)$$

This revised allocation ratio is based on the point of a controllable zone rather than controllable range because the commander is more interested in an area of control, rather than merely a controllable range. As controllable range is increased, controllable zone is also increased. Referring to this point, the allocation ratio is represented as :

$$a = C_0 \left[1 + \frac{V_p}{V_w} \left(\frac{t_a}{t_w} - 1 \right) \right]^2 \quad (3-6)$$

Where, C_0 = arbitrary constant and

$$\text{Revised controllable range} = \left[1 + \frac{V_p}{V_w} \left(\frac{t_a}{t_w} - 1 \right) \right]^2 \quad (3-7)$$

In equation 3-7, the allocation ratio is a function of available time because all terms are constant except available time. Therefore, the greater the available time is, the more the controllable zone.

If the command and control system is reinforced, available time is increased and the controllable zone is also expanded. The equation of the allocation ratio after reinforcement in C_2 system is as below. [Paek, 2002]

$$\delta a = C_0 \left[1 + \frac{V_p}{V_w} \left(\frac{t_{aa}}{t_w} - 1 \right) \right]^2 \quad (3-8)$$

Where, t_{aa} = Increased available time after reinforcement

δ = Factor of dense force or incremental attrition of allocation ratio and this equation satisfies next condition,

a (the allocation ratio before reinforcement) $< \delta a$ (the allocation ratio after reinforcement) (where, $\delta > 1$)

3. The Exchange Rate

The third MOE factor in C^2 theory is the exchange rate. The enhanced C^2 system can improve a platform's individual effectiveness. The exchange rate is directly related to the probability of survival. The probability of survival may increase by decreasing command and control time, which can enable quicker reaction and reduce damage from enemy attack before the enemy is prepared damage to the other force. As a result, exchange rate can also increase by coefficient γ . Therefore the exchange rate is as below. [Paek, 2002]

$$\gamma X_0 = C_3 \{1 + C_1 \rho \sigma^2 [V_p t_{cs}^2]\} \quad (3-9)$$

Where, C_1, C_3 = Arbitrary constant

X_0 = Exchange rate

ρ = density of enemy

σ^2 = initial accuracy of information

V_p = Speed of platform

γ = Coefficient of exchange rate that represents the improvement of enhanced C^2 system

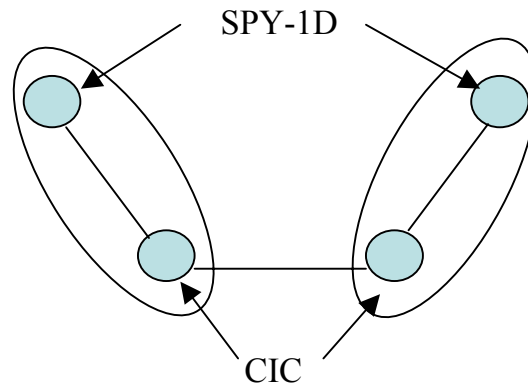
X_0 (the exchange rate before reinforcement) $< \gamma X_0$ (the exchange rate after reinforcement) (where, $\gamma > 1$)

B. MODEL ENHANCEMENT

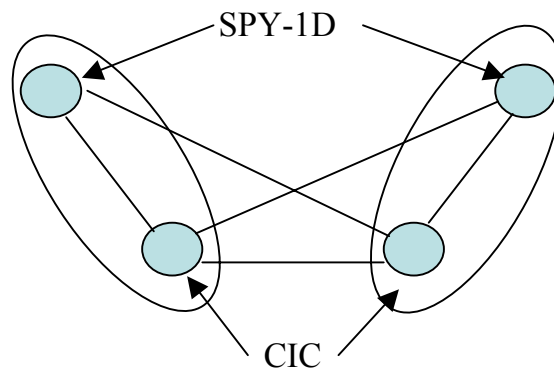
1. Abstract of Three Kinds of C^2 Process

The difference among Cooperative Engagement Capability (CEC), Network Centric Warfare (NCW) and Platform Centric Warfare (PCW) is the informational link between platforms. PCW links each other through only CIC (Combat Information Center). NCW links radar and CIC within all platforms, so that each platform can share information in real time. That is, PCW cannot share information, but NCW can share Common Operation Picture (COP). CEC is distinguished by Central Control (CC). CC of

CEC system can decide and assign air defense mission to individual platform automatically. The graphical representation of each C² process is in Figure 6, with spy-1D being the particular sensor.



Platform-Centric : *divided duties*



Network-Centric :
Common operating picture

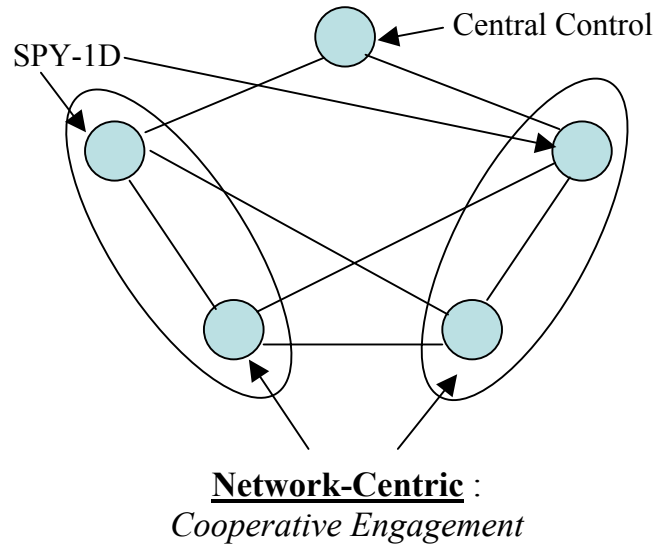


Figure 6. Three Operation Processes [From RAND, 2002]

2. Concept of New MOE Model

Schutzer anticipated the enhancement of C^2 systems 21 years ago. He estimated that enhanced C^2 systems could reduce the time that the commander spent deciding during engagement. He suggested an MOE impacted by enhanced C^2 systems, but he did not define time impact and information in detail. I analyze and define this time impact information with CEC and NCW C^2 processes because both of these two processes are enhanced C^2 systems. In other words, these can shorten the commander's decision time and improve information superiority. As mentioned above, I will develop possible factors that impact decision time, and apply them to CEC, NCW and PCW. In addition to the time factor, information and controllable range are important but abstract factors in Schutzer's theory. Therefore, I will analyze these factors in detail.

3. Analysis of Three Parameters

As mentioned above, the MOE of C^2 system is affected by the type of the operating process. I modify three factors that are contained in the MOE (probability of survival, allocation ratio, and exchange rate) using three significant parameters. One of these parameters is decision time. I introduce two new parameters to modify decision

time. These are information certainty and human factor. The figure below is a representation of these factors, parameters and their relationships. Available time is discussed later in the chapter.

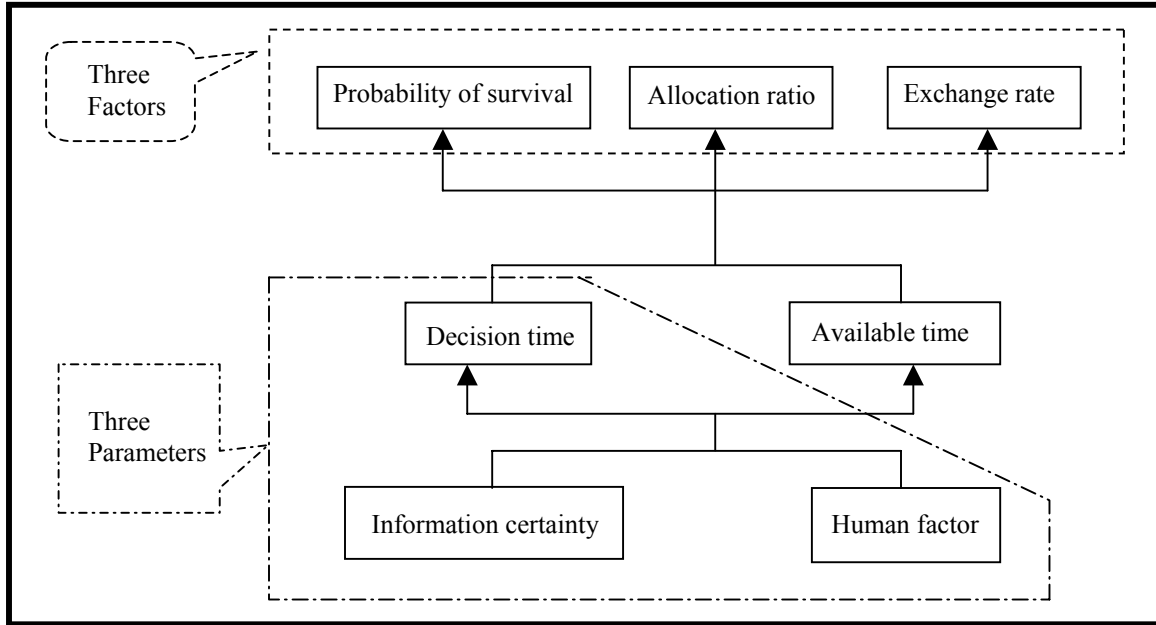


Figure 7. Three Factors and Three Parameters.

a. Assumptions

I proceeded with three basic assumptions. First, the scenario in this study is restricted to air defense. I make this assumption because CEC is developed for the purpose of air defense. While NCW and CEC C^2 processes should be beneficial to both defense and attack, the commander in the attack has more decision time than defense, as he be able to choose attack time and place, and therefore is less reliant on extending decision time.

The second assumption stems from the fact that air defense decision is made by the task force commander. When missiles are coming directly at a friendly ship, the individual ship defends itself without reporting to task force commander. But the goal of developing command and control systems is to foresee and preempt an attack. NCW and CEC are expected to provide the capability to detect the enemy from long distance and respond before a threat comes closer. Therefore, I assume that individual ships must

report to the task force commander if any ship detects incoming missile. Then, the commander decides and assigns the air defense mission and the assigned ship counterattacks against incoming missile.

Third, I assume every ship in task force can cover other ships, and task force commander assigns one incoming missile to each ship. This requires ships to be located closely together, but enable the task force commander to avoid assigning more than two rounds of incoming missile to individual ship.

This study does not assert that more dense ship stationing, which supports mutual defense, is superior to more dispersed force formation. It simply focuses on the mutual defense scenario for analysis.

b. Analysis of Decision Time

Decision time(t_{cs}) is the time available for the task force commander from sensing to deciding. It is the same time duration from T_0 until T_c in Figure 7, as defined by Schutzer. I redefine this time duration into three terms, which are Report time(t_{rt}), Tactical decision time(t_{tdt}) and Order time(t_{ot}). Thus, the decision time(t_{cs}) is

$$t_{cs} = t_{rt} + t_{tdt} + t_{ot} \quad (3-10)$$

Report time(t_{rt}) is the communication time to report incoming missile information from the individual ship that detects missiles to task force commander. I model t_{rt} for each version of C^2 as seen below.

- PCW: The time to report changes with individual speech speed, communication stability, and so forth. However, the difference between individual is expected to be very small. Therefore, I set it as a constant (C_2).
- NCW and CEC: I set t_{rt} in NCW and CEC as ‘zero’. CEC and NCW share COP in real time, so task force commander can notice air threat without reports from individual ships. Therefore, individual ships need not report to task commander. Therefore, report time(t_{rt}) is

PCW: C_2

NCW and CEC: ‘0’

Tactical decision time (t_{dt}) is the time from report to the decision by the commander. This tactical decision time is related to maximum reaction time (t_r). Maximum reaction time is the maximum available time to decide from detection air threats until firing anti air missile. Commander has to make a defensive decision within maximum reaction time. I assume that the commander makes tactical decisions with two important resources, which are accurate information certainty (I) and human factor (h). The task force commander needs information to make the best tactical decision. Given accurate information, the commander decides easily and quickly. Decision time also changes with human factor. Human factor is difficult to quantify. It relates to the level of training, strategic knowledge, tactical experience, personal character, and so forth. All these factors converge into what I call human factor. For instance, a task force commander who is well trained and has a wealth of strategic knowledge and experience can be expected to make a decision easily and quickly. I regard this as optimistic scenario. Therefore, decision time will be decreased as information certainty increases and human factor rating improves. Since, CEC can decide and distribute air defense mission assignment order automatically, it has no human dimension. Therefore, decision time is

$$\text{NCW and PCW: } t_{dt} = \frac{t_r \times h}{I} \quad (3-11)$$

$$\text{CEC: } t_{dt} = \frac{t_r}{I} \quad (\text{No human factor}) \quad (3-12)$$

Where, I : Information certainty ($I \geq 1$)

h : Human factor (Optimistic $0 < h < 1$ Pessimistic)

t_r : Maximum reaction time

Order time (t_{ot}) is communication time from task force commander to individual ship, which is essentially report time (t_{rt}), but the communication time is in the opposite direction. It is the time to deliver task force commander's decision. But it differs among the three C² processes:

- NCW and PCW: I assume that t_{ot} is small, but consistent, so it is treated as constant (C_3).
- CEC : I set t_{ot} at zero, because CEC can distribute decision automatically.

Therefore, order time(t_{ot}) is

$$\begin{aligned} \text{NCW and PCW} &: C_2 \\ \text{CEC} &: 0 \end{aligned}$$

After analyzing the task force commander's decision time from the point of view of these three main factors, I found that commander's decision time(t_{dt}) is the most significant. Essentially, the other two factors(t_{rt} , t_{ot}) can be treated as constant or '0'. Therefore, decision time(t_{cs}) for each C^2 mode is defined as:

$$\text{PCW: } t_{cs} = C_2 + \frac{t_r \times h}{I} + C_3 = \frac{t_r \times h}{I} + C_4 \quad (3-13)$$

$$\text{NCW: } t_{cs} = \frac{t_r \times h}{I} + C_3 \quad (3-14)$$

$$\text{CEC: } t_{cs} = \frac{t_r}{I} \quad (3-15)$$

c. *Analysis of Information Certainty and Human Factor*

Information certainty(I) implies potential value of network. If a network has an increased number of sources and nodes, information certainty is assumed to be improved. Another assumption is that entire network is connected each other firmly, and I assume that network has no loss of potential value. This is especially true for CEC due to its superior grid lock and correlation algorithms, as discussed in Chapter II. In order to estimate potential value of network, I use the 'Metcalfé's law'. Metcalfé's law states that "The source of potential value is a function of the interactions between the nodes. For every 'n' node in a network, there are 'n-1' potential interactions between the nodes. Therefore, the total number of value creating interaction is $n^2 - n$. For large n, the potential value scales with n^2 ." [CCRP, 2000]

The number of nodes in task forces differs according to C^2 operating process. PCW has no interaction among ships in task force, and has only 1 node. The number of nodes in NCW is the same as the number of ships in a task force because all ships interact. Finally, the number of nodes in CEC is always greater than the number of ship by 1, because CEC has the ‘central control’ in a task force. This relationship is seen in Figure 6.

Number of ship	Number of node		
	PCW	NCW	CEC
N	1	N	N+1

Table 1. Number of Node in Operation Process.

The potential value of each C^2 operating process is summarized in Table 1, based on Metcalfe’s law. Information certainty means the potential value of Metcalfe’s law. In other words, the more interaction in an operating process, the more information it has. Increased information certainty should improve the value of MOE. As shown in the figure below, information certainty remains similar between NCW and CEC, but PCW remains fixed at one.

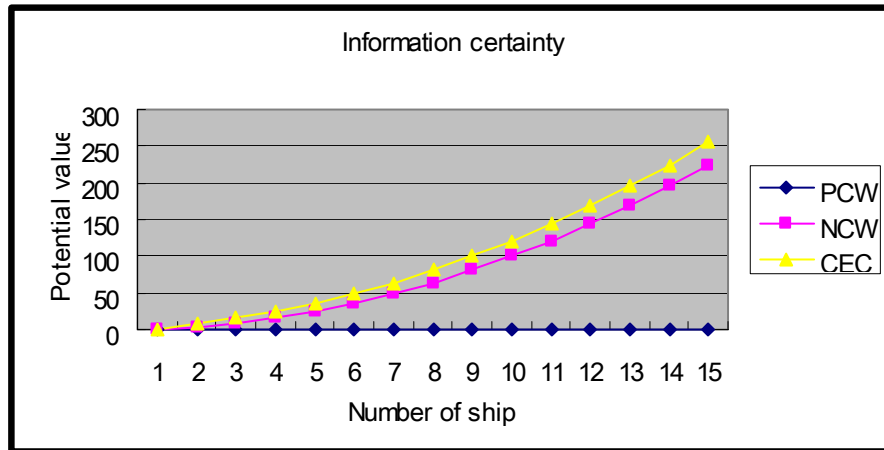


Figure 8. Information Certainty with Applying Metcalfe’s Law.

In order to compare the human factor component of decision time, it is important to consider the air defense operation procedures for each C^2 methodology. I assume that a task force commander with NCW or CEC system detects an air threat using

the common operating picture (COP). An individual ship with PCW has to report to commander. A commander with PCW or NCW makes the overall tactical decision and assigns defense mission to one of its ships in task force. The ship assigned fires an anti air missile. This implies that there is a human factor. I demonstrate the effect of information certainty and human factor on decision time in the figure below.

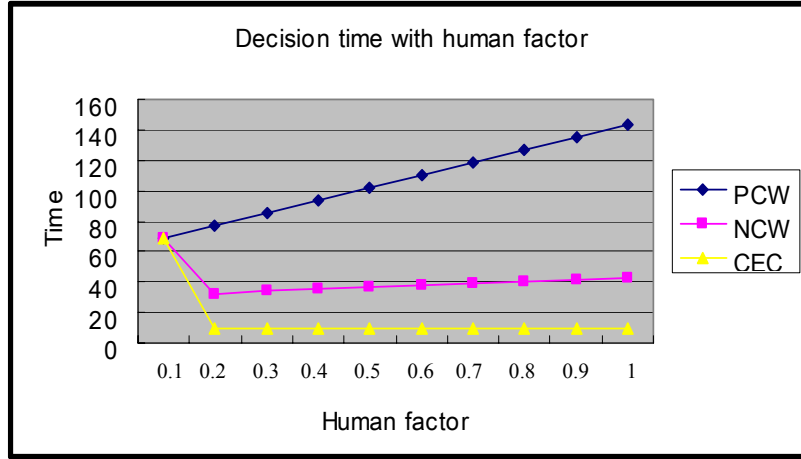


Figure 9. Decision Time with Human Factor.

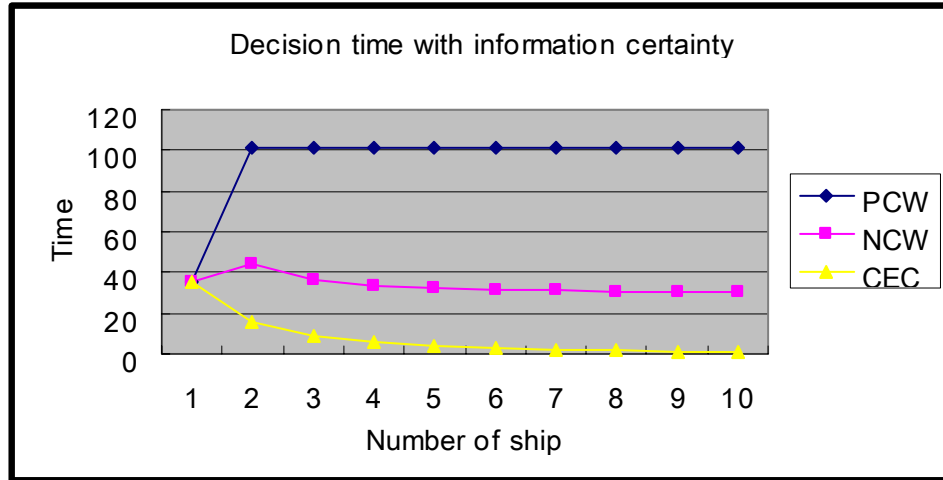


Figure 10. Decision Time with Information Certainty.

Specifically, from equations 3-13, 3-14, and 3-15, I calculate t_{cs} for each C^2 system, while varying the value of human factor or uncertainty. As seen in Figure 10, the decision time of PCW increases as human factor of commander becomes pessimistic, with constant 3 ships. For example, commander who is absolutely pessimistic (1) uses the

maximum decision time that he can spend. He has little confidence in his decision. This delay of decision time should result in the reduction of the probability of survival. It is also related to available time.

On the other hand, the absolutely optimistic commander shows similar results in NCW and CEC. Figure 10 shows the effect of varying the number of ships when human factor is constant. PCW has the same decision time because it has just 1 node regardless of the number of ships. In other words, information certainty for PCW is not affected by number of ships. Decision time of NCW and CEC is decreased by increment of the number of ship.

d. Analysis of Available Time

The available time (t_{at}) as described by Schutzer, means how much time the task force has available from deciding response until execution of response. It is the surplus time from threat detection to react time. It contributes by addressing the controllable range (r_c) of task force or individual ship. It can be represented as shown below.

$$t_{at} = t_r - t_{cs} \quad (3-16)$$

Where, t_r : Maximum reaction time

t_{cs} : Decision time

By applying equations 3-13/14/15 into 3-16, the equation of available time becomes:

$$\text{PCW: } t_{at} = t_r - \frac{t_r \times h}{I} - C_4 \quad (3-17)$$

$$\text{NCW: } t_{at} = t_r - \frac{t_r \times h}{I} - C_3 \quad (3-18)$$

$$\text{CEC: } t_{at} = t_r - \frac{t_r}{I} \quad (3-19)$$

Where, $\forall t_{at} \geq 0$

Therefore, shorter decision time needed by the task commander to make a decision increases the available time to act. The available time is directly inverse of

decision time. The interesting fact is that commander can spend this available time usefully. This variance in available time may greatly influence the engagement result. It also affects controllable range and it affects allocation ratio.

4. Implementation of Three Factors to the Elementary Equation of MOE in C^2 Theory

Based on the equations developed above, I implement three factors (decision time, information certainty and available time) into three elementary equations (probability of survival, allocation ratio and exchange rate) of MOE in C^2 theory.

a. Implementation to the Probability of Survival

Schutzer's original probability of survival equation is

$$\alpha P_{kj} = \frac{1}{1 + C_1 [V_p \sigma^2 t_{cs}]^2} \quad (3-3)$$

Where, C_1 = Arbitrary constant

α = Coefficient of the probability of survival

V_p = Speed of enemy platform

σ^2 = Initial information accuracy

In this equation, I assume V_p and σ^2 as essentially constants. The speed of enemy platform (V_p) toward the friendly force may change little; initial information accuracy (σ^2) includes enemy distribution, probability of detection, sensor accuracy (capability), methodologies to detect (ship mounted radar, air craft, UAV) and so forth. These two parameters are important but are assumed to have little relation with time impact. I substitute decision time (t_{cs}) into the equations of 3-13/14/15. The modified equations are shown below.

$$\text{PCW: } P_{kj} = \frac{1}{1 + C_1 [V_p \sigma^2 (\frac{t_r \times h}{I} + C_4)^2]} \quad (3-20)$$

$$\text{NCW: } \alpha P_{kj} = \frac{1}{1 + C_1 [V_p \sigma^2 (\frac{t_r \times h}{I} + C_3)^2]} \quad (3-21)$$

$$\text{CEC: } \alpha P_{kj} = \frac{1}{1 + C_1[V_p \sigma^2 (\frac{t_r}{I})^2]} \quad (3-22)$$

Based on the equations above, I compare the probability of survival among the three C² processes. Figure 11 shows the effect of human factor with constant number of 3 ships. The probability of survival of CEC remains constant, because CEC has no human factor. The difference between CEC and NCW and between CEC and PCW is large because the value of decision time (t_{cs}) is square in the denominator. Therefore, CEC has definite potential of enhancing C² systems.

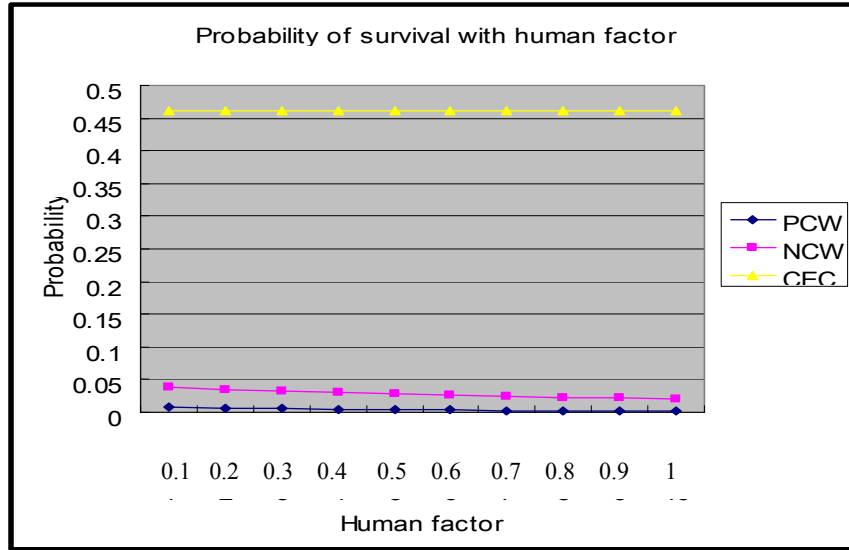


Figure 11. Probability of Survival with Human Factor.

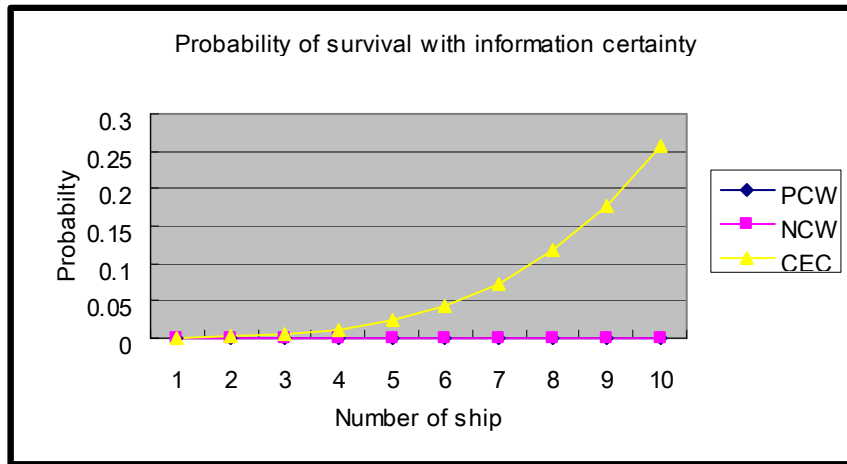


Figure 12. Probability of Survival with Information Certainty.

Figure 12 shows the change in probability of survival as information certainty varies. The probability of survival of CEC increases rapidly with increased in information certainty but PCW and NCW maintain similar low probability. This implies that CEC is most effective with a large task force.

b. Implementation to the Allocation Ratio

Schutzer's equation of the allocation ratio is

$$\delta a = C_0 \left[1 + \frac{V_p}{V_w} \left(\frac{t_{aa}}{t_w} - 1 \right) \right]^2 \quad (3-8)$$

In this equation, Schutzer did not define V_p (platform velocity), V_w (weapon flight velocity) and t_w (maximum weapon flight time) in detail. I regard these (V_p , V_w , and t_w) as arbitrarily constant because these values are assumed to vary only slightly among threats. I substitute t_{aa} (increased available time) with t_{at} , as available time. After applying equation 3-17/18/19 with simple algebra, the modified allocation ratio becomes

$$\text{PCW: } a = C_0 \left[1 + \frac{V_p}{V_w} \left(\frac{t_r(I-h) - IC_4}{It_w} - 1 \right) \right]^2 \quad (3-23)$$

$$\text{NCW: } \delta a = C_0 \left[1 + \frac{V_p}{V_w} \left(\frac{t_r(I-h) - IC_3}{It_w} - 1 \right) \right]^2 \quad (3-24)$$

$$\text{CEC: } \delta a = C_0 \left[1 + \frac{V_p}{V_w} \left(\frac{t_r(I-1)}{It_w} - 1 \right) \right]^2 \quad (3-25)$$

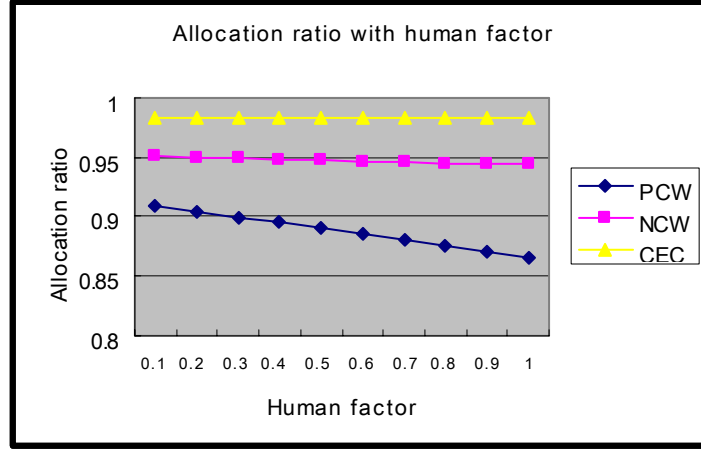


Figure 13. Allocation Ratio with Human Factor.

The allocation ratio based on the three C^2 processes shows that PCW (Figure 13) varies more with human factor relative to NCW and CEC. However, human factor has little effect regarding the allocation ratio of NCW and CEC.

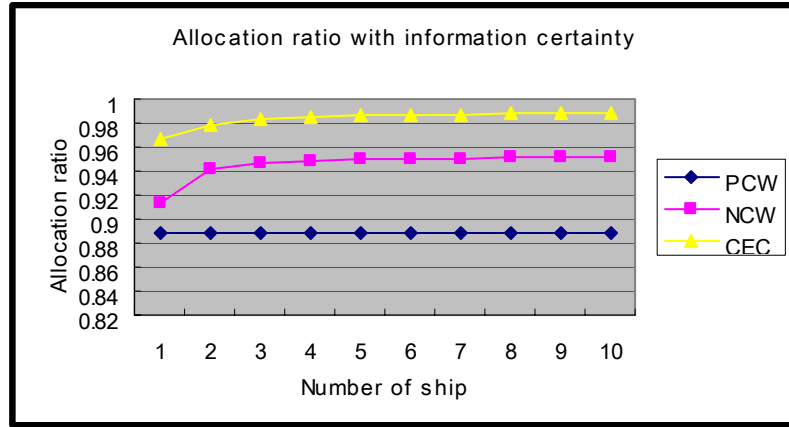


Figure 14. Allocation Ratio with Information Certainty.

Figure 14 shows the relationship between allocation ratio and information certainty (number of ship). It is clear that information certainty has a little effect on allocation ratio, meaning that information certainty will be unlikely to improve the ability of a task force commander to concentrate his forces.

c. *Implementation to the Exchange Rate*

Schutzer's equation of the exchange rate is

$$\gamma X_0 = C_3 \{1 + C_1 \rho \sigma^2 [V_p t_{cs}^2]\} \quad (3-9)$$

In this equation, ρ (enemy distribution), σ^2 (initial information accuracy) and V_p (platform velocity) are set as arbitrarily constant. I substitute arbitrary constant C_3 with C_5 to avoid confusion because I used C_3 in the equation of decision time. After applying equation 3-13/14/15, then modified exchange rate is

$$\text{PCW: } X_0 = C_5 \left\{ 1 + C_1 \rho \sigma^2 \left[V_p \left(\frac{t_r \times h}{I} + C_4 \right)^2 \right] \right\} \quad (3-26)$$

$$\text{NCW: } \gamma X_0 = C_5 \left\{ 1 + C_1 \rho \sigma^2 \left[V_p \left(\frac{t_r \times h}{I} + C_3 \right)^2 \right] \right\} \quad (3-27)$$

$$\text{CEC: } \gamma X_0 = C_5 \left\{ 1 + C_1 \rho \sigma^2 \left[V_p \left(\frac{t_r}{I} \right)^2 \right] \right\} \quad (3-28)$$

I compare the exchange rate among three operation processes graphically below. Figure 15 shows that when only considering human factor, the exchange rate of NCW and CEC has little difference, but the exchange rate of PCW increases sharply with higher value for human factor. Human factor can greatly influence exchange rate of PCW but influence little on NCW and CEC. Figure 16 shows that after adding the number of ships, exchange rate of NCW and CEC change slightly but PCW is not changed. As a result, PCW is affected by only human factor, but NCW and CEC are little affected by the information certainty and human factor at the same time.

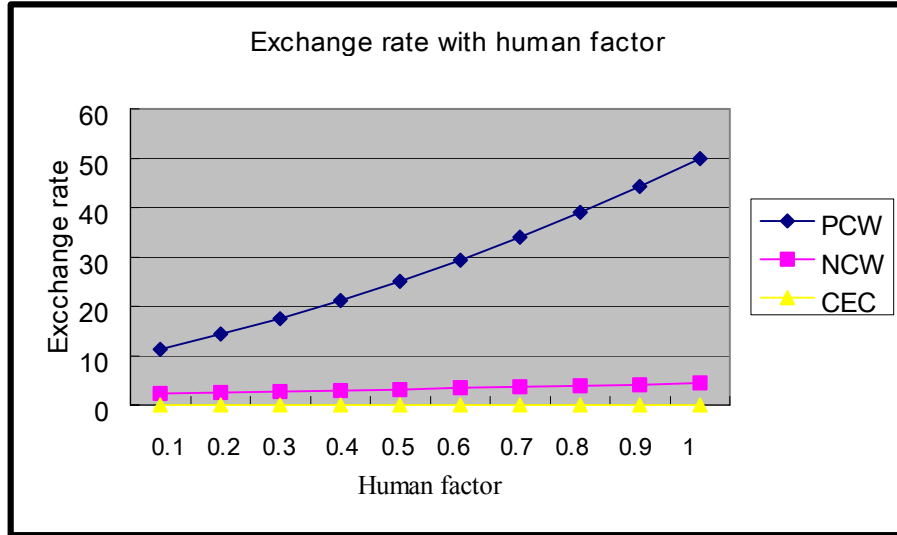


Figure 15. Exchange Rate with Human Factor.

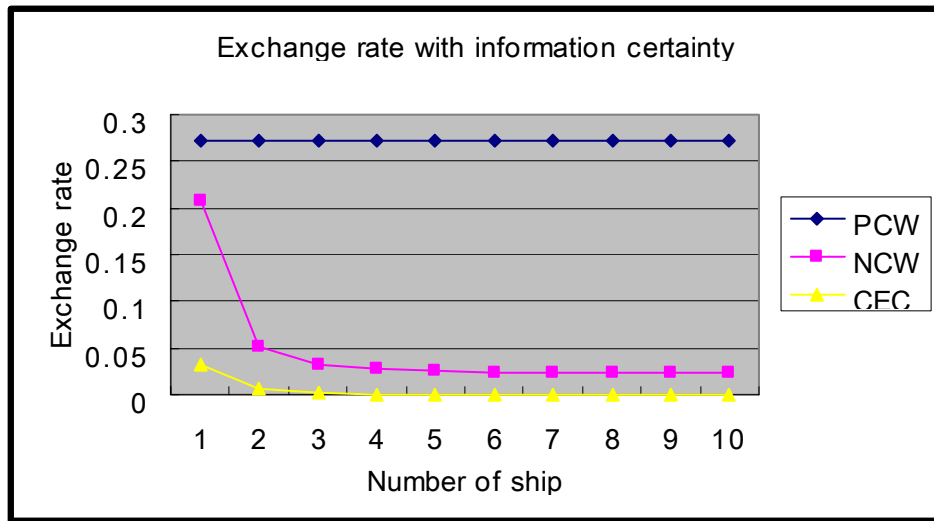


Figure 16. Exchange Rate with Information Certainty.

5. Implementation to MOE in C^2 Theory

I analyzed three factors, parameters and three elementary equations which are used to modify MOE in C^2 theory. Each equation shows the effect of decision time as it depends on information certainty and human factor. However, it is difficult to understand the overall improvement caused by enhanced C^2 system with each individual equation. Therefore, I estimate the improved MOE by modifying the original MOE equation in Schutzer's C^2 theory. The Schutzer's MOE equation is

$$MOE_j = \frac{\langle N_j^2 \rangle - \langle M_j^2 \rangle}{N_0^2} \quad (3-29)$$

Where, $\langle N_j^2 \rangle$ = The value of blue remaining force after j^{th} engagement

$\langle M_j^2 \rangle$ = The value of red remaining force after j^{th} engagement

$\langle N_0^2 \rangle$ = The value of total initial of blue and red forces in the specific j^{th} engagement.

The elements of above MOE equation is as below,

$$\langle N_j^2 \rangle = \sum_{k=1}^T \sum_{k'=1}^S \frac{P_{kj} a_{kj} n_{kj}^2}{1 + X_{kk'}} \quad (3-30)$$

$$\langle M_j^2 \rangle = \sum_{k=1}^T \sum_{k'=1}^S \frac{X_{kk'} q_{k'j} b_{k'j} m_{k'j}^2}{1 + X_{kk'}} \quad (3-31)$$

$$\langle N_0^2 \rangle = \sum_{k=1}^T \sum_{k'=1}^S n_{kj}^2 \quad (3-32)$$

Where, k = the number of unit in each types of blue force

k' = the number of unit in each types of red force

P_{kj} = the probability of survival in j^{th} engagement

a_{kj} = the allocation ratio of each types of blue force in j^{th} engagement

$X_{kk'}$ = the exchange ratio of k unit blue force to k' unit of red force which means the loss of blue force to the loss of red force during engagement

$q_{k'j}$ = the probability of survival of red force

$b_{k'j}$ = the allocation ratio of red force

n_{kj} = the number of unit blue force in j^{th} engagement

$m_{k'j}$ = the number of unit red force in j^{th} engagement

Schutzer suggested the MOE model is improved by enhanced C^2 system as shown below.

$$MOE = \frac{\alpha^2 \delta^2 \langle N^2 \rangle - \beta^2 \xi^2 \gamma X_0 \langle M^2 \rangle}{N^2} \quad (3-33)$$

Assuming the probability of survival, allocation ratio and exchange rate are independent of type of ship k and engagement j , Schutzer generalized the variables and remove subscripts. Therefore, substituting the variables for N and M from equations 3-31 and 3-32 into equation 3-33, following some algebra, the result is:

$$MOE = \frac{(\alpha p)^2 (\delta a)^2 N^2 - (\beta q)^2 (\xi b)^2 \gamma X_0 M^2}{N^2} \quad (3-34)$$

Using equation 3-34, I find out how much the MOE increases with enhanced C^2 system. I assume three simple engagement situations, where two naval task forces engage, with N representing blue force and M representing red force. Both forces have same number and class. The only difference is the C^2 system. Three situations are:

Situation 1: Blue force with NCW against Red force with PCW

Situation 2: Blue force with CEC against Red force with PCW

Situation 3: Blue force with PCW against Red force with PCW

I consider the effect of information certainty and human factor at the same time. The information certainty of task force increases, while the human factor becomes pessimistic. I estimate MOE by situation. The graph below represents the MOE with operating processes.

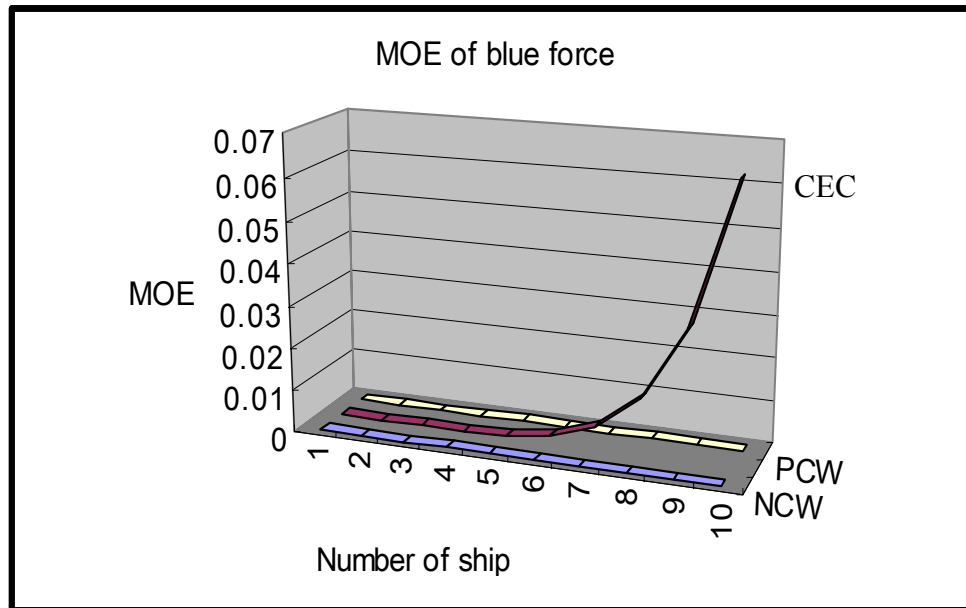


Figure 17. MOE of Blue Force with the Information Certainty (Number of Ship).

Figure 17 show that CEC increases significantly as the number of ships increases. Therefore, I conclude that CEC is dominant C^2 system.

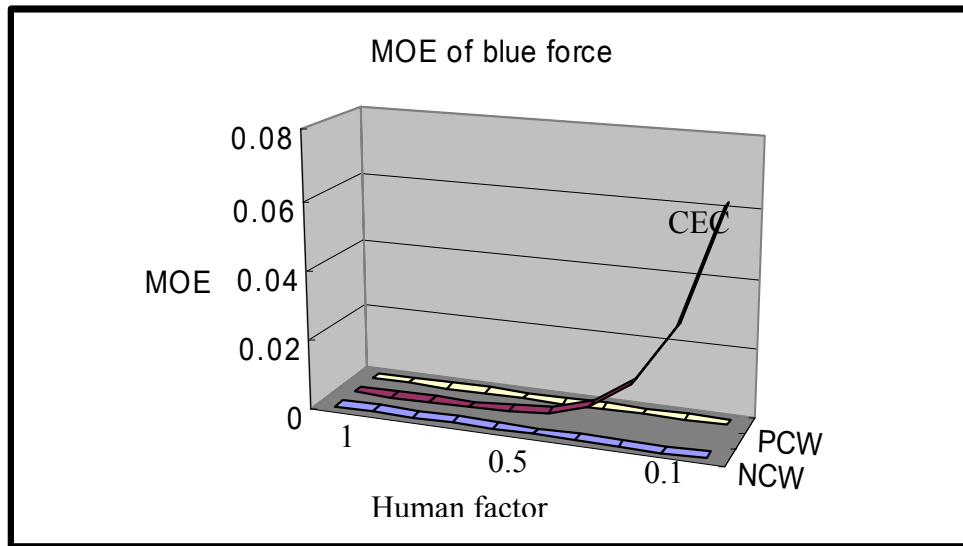


Figure 18. MOE of Blue Force with Human Factor.

Figure 18 supports the dominance of CEC, too, where human factor becomes optimistic contrary to Figure 17 and the information certainty is the same throughout. On these conditions, the graph shows that the MOE of NCW and PCW is still low and MOE of CEC increases as human factor becomes optimistic. These figures show that CEC is not affected by human factor, but rather by only information certainty, and its contribution to MOE is evident.

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IV. SIMULATION AND OUTPUT ANALYSIS

A. PURPOSE OF SIMULATION

In Chapter III, I discussed an improved MOE and studied its appropriateness with an analytical model. The results show that CEC is the most effective C^2 system, NCW is next best and PCW is the least effective operating process. The probability of survival, allocation ratio and exchange rate make up this MOE. The prominent factors of these equations are decision time, information certainty and human factor. In my streamlined model, the difference among C^2 operating processes is a result of these three parameters. Decision time and information certainty were shown to affect MOE significantly, but human factor appeared to have little effect on CEC and NCW. A weakness of this analytical model is that it is limited by its static and deterministic inputs. I therefore build a spreadsheet simulation that can include randomness in battle outcomes, as well as allowing for an experimental design that can examine the range of input parameters, the magnitude of factor, main effects and possible interactions.

B. SCENARIO

The scenario concerns group air defense performed under the task force commander. Red force maneuvers to invade blue force without proclamation of war. Blue force conducts reconnaissance and observes red force intention and movement. I have several assumptions to transfer scenario into simulation model.

Red force eventually (see Figure 19) attacks with its missiles and blue force defends against incoming missiles to survive. Air defense operation is performed by task component commander. Each ship has the responsibility to detect and report incoming missile. The task force commander integrates target information, analyzes the air threat, decides upon an appropriate action, and allocates defense mission. The ship assigned to the mission fires anti air missile without delay. However, there is one exceptional case. If the enemy missile comes directly at a ship, and the individual ship detects a short distance from its position, the individual ship commander defends itself.

Red force capability is represented by inter arrival time of incoming missile. If the red force has strong combat strength, the inter arrival time is short. On the other hand, if

red force is killed by blue force counter attack, inter arrival time becomes larger. The other two variables in the simulation are I , information certainty, and h , the human factor. The response variable for this simulation is the number of surviving blue ships.

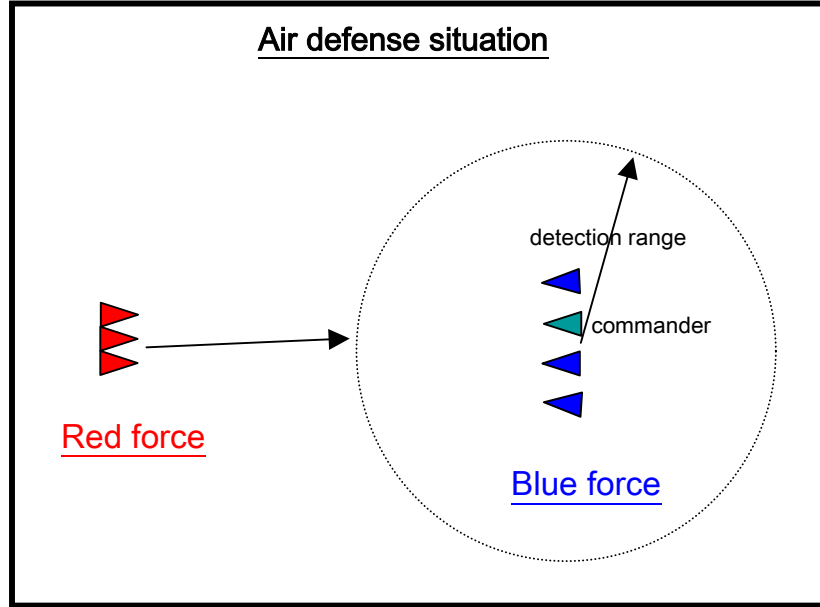


Figure 19. Air Defense Situation.

C. ASSUMPTIONS

(1) I do not explicitly model Red force ships in the enemy task force, but rather the amount of missiles they have and their frequency of firing. The interarrival time between incoming missile and quantity represents Red force size and capabilities.

(2) Blue force is consisted of same type of AEGIS platform. Each ship has same detection probability of detecting missile and same probability of kill of anti air missile.

(3) Task force commander allocates defense mission as one ship to one missile to maintain defense capability equally in task force. AEGIS platforms can counterattack against several incoming missile at one time. Task force commander wants to detect at a long distance, to reduce individual platform responsibility for defense and control entire task force missile inventory to expand chance to engage, by distributing the mission across the force.

(4) Each ship will be sunk or neutralized after two hits by a missile which occurs when a missile arrives at a ship before it finishes its defense mission.

D. SIMULATION DESCRIPTION

I examined the probability of survival with simulation to estimate the effect of the three different C^2 systems on the enhancement coefficient α . I also address the updated MOE as described at the end of Chapter III, and the relation among three factors (decision time, information ratio and human factor) and the probability of survival.

The probability of survival equation contains three parameters, as discussed earlier. These are platform velocity (V_p), initial information accuracy (σ^2) and decision time (t_{cs}).

$$\alpha P_{kj} = \frac{1}{1 + C_1 [V_p \sigma^2 t_{cs}^2]} \quad (3-3)$$

As with my analytical model, I focused on decision time for simulation because of the importance of time in the commander's decision, and because the other two variables can be held constant for a specific scenario. Decision time, as discussed in Chapter III, depends on information certainty and human factor. Decision time is as shown below.

$$\text{PCW: } t_{cs} = C_2 + \frac{t_r \times h}{I} + C_3 = \frac{t_r \times h}{I} + C_4 \quad (3-13)$$

$$\text{NCW: } t_{cs} = \frac{t_r \times h}{I} + C_3 \quad (3-14)$$

$$\text{CEC: } t_{cs} = \frac{t_r}{I} \quad (3-15)$$

In order to simulate, I apply concept of queuing model. A typical queuing model consists of customer and their arrival times, servers and their service time, a representation of server "interaction" (parallel or series) and a method of handling anticipated queues. These representations are summarized below.

Queuing model Component	Scenario
Customer	Incoming missile
Inter arrival time	Uniform arrival time
Server	Friendly ship
Server allocation	Parallel
Service time	Decision time
Queue	No queue

Table 2. Simulation Model Description.

An important concept from this table is that this simulation model does not allow a queue. A missile that is not serviced hits the blue ship, representing the enemy's success. Another important concept is the assumptions of inter arrival time of incoming missile. I used a uniform distribution for inter arrival times. I use decision time as service time. Defense time against incoming missile mainly depends on decision time; anti air missile flight time does not affect defense time.

Two of the input variables in this model are the parameters in the decision time (t_{cs}) equation. Decision time is calculated with information certainty and human factor. As discussed in Chapter III, information certainty (I) depends on the number of ships in task force and human factor depends on individual character. The third input variable is the missile arrival rate. The simulation output is the number of surviving ships after missile defense. The criterion is simple and fully reasonable.

E. EXPERIMENTAL DESIGN

The simulation experiment has three objectives. First, I want to determine the statistical significance of each of the three factors mentioned above (information certainty, human factor, and missile inter arrival rate) as well as any interaction among parameters. Second, I want to determine on approximate value for α , the coefficient that modifies probability of survival, as suggested by Schutzer. Third, I want to determine if there are statistically significant difference among the 3 modes of C^2 (PCW, NCW, and CEC) as observed in the simulation.

In order to get reasonable simulation output, I have to determine the appropriate value of parameters within the scenario.

PCW		Scenario setting		
		Low(-1)	Medium(0)	High(1)
Parameters	Inter arrival time (Uniform)	0 ~ 15	0 ~ 10	0 ~ 5
	Information certainty (I)	1	1	1
	Human factor (h)	0.1	0.6	0.9
Number of ship		3	6	10

Table 3. Scenario Setting of PCW.

The levels or values used for each of the parameters represent specific scenario settings, as seen in Table 3. The inter arrival times represent the capabilities of the enemy force, particularly the number and strength of enemy ships. The low inter arrival time represents enemy capability is weak, the medium represents intermediate capability, and the high implies that the strong capability. I assume maximum number of ships in a task force is 10, with the minimum number of ship set at 3, and the medium at 6. The information certainty (I) of PCW is always '1', as discussed in Chapter III. Human factor (h) setting ranges from 0.1 to 0.9. The low (optimistic) is 0.1, medium value is 0.6 and high (pessimistic) value is 0.9. A low number for human factor results in enhanced decision time and high number of human factor reduces decision time.

NCW		Scenario setting		
		Low(-1)	Medium(0)	High(1)
Parameters	Inter arrival time (Uniform)	0 ~ 15	0 ~ 10	0 ~ 5
	Information certainty (I)	9	36	100
	Human factor (h)	0.1	0.6	0.9
Number of ship		3	6	10

Table 4. Scenario Setting of NCW.

Table 4 shows the scenario setting of NCW. The difference between PCW is the value of information certainty. Information certainty of NCW is relative to the number of ship and it increases by number of ship.

CEC		Scenario setting		
		Low(-1)	Medium(0)	High(1)
Parameters	Inter arrival time (Uniform)	0 ~ 15	0 ~ 10	0 ~ 5
	Information certainty (I)	16	49	121
	Human factor (h)	0.1	0.1	0.1
Number of ship		3	6	10

Table 5. Scenario Setting of CEC.

Table 5 shows the scenario setting of CEC. The particular difference with PCW and NCW is that CEC setting has always high value of human factor term such as dummy variable for consistency of simulation design even if human factor does not affect CEC.

I will use a 3^3 factorial design, meaning there are three parameters under observation each at three levels. [Montgomery 1984] The three parameters are interarrival time, information certainty and human factor. Three levels correspond to low, medium and high setting. With three parameters at three levels each, there are a total of 27 design points, or treatments. I use coded variables parameter setting according to the level (1=high, 0=medium, -1=low) instead of the actual value to make the design simple.

Design point	Parameter setting		
	Inter arrival time	Information certainty	Human factor
1	1	1	1
2	1	1	0
3	1	1	-1
4	1	0	1
5	1	0	0
6	1	0	-1
7	1	-1	1
8	1	-1	0
9	1	-1	-1
10	0	1	1
11	0	1	0
12	0	1	-1
13	0	0	1
14	0	0	0
15	0	0	-1
16	0	-1	1
17	0	-1	0
18	0	-1	-1
19	-1	1	1
20	-1	1	0
21	-1	1	-1
22	-1	0	1
23	-1	0	0
24	-1	0	-1
25	-1	-1	1
26	-1	-1	0
27	-1	-1	-1

Table 6. Experiment with Design Point.

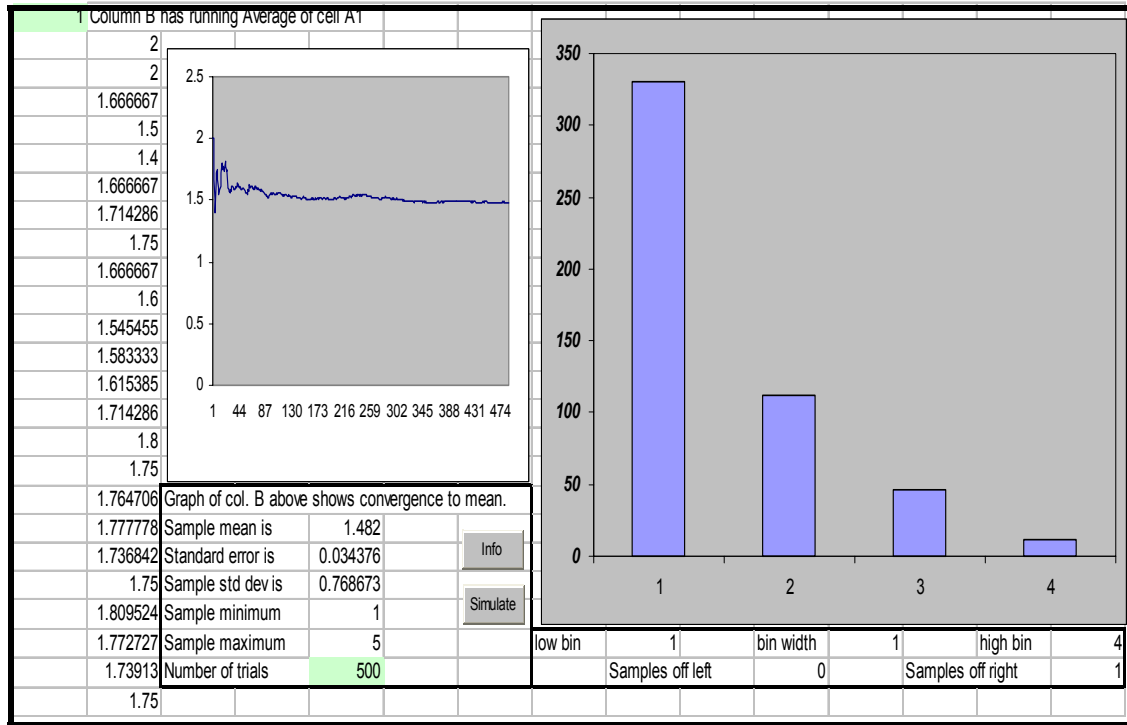


Figure 20. Result of Simulation with **Simsheet**.

The simulation used is a spreadsheet tool developed by Professor Alan Washburn of NPS as an Excel Addin. As seen in the figure above, the numbers on the left represents the number of remaining ships after air defense at each run. The small graph shows the expected number of remaining ship converging to a specific value. The box below it shows the sample mean, standard error, standard deviation, sample minimum and maximum. In above graph, the expected number of remaining ship is 1.5 and standard deviation is 0.768673. The right hand side histogram shows the frequency of different number of remaining ship. The frequency of 1 ship remaining is over 300 and 4 ships remaining approximately about 20 times. The small number of remaining ships represents the probability of survival of is small.

F. SIMULATION OUTPUT SUMMARY

In order to determine a reasonable estimate of the expected number of surviving ships for each C^2 process, I simulated each design point 100 times. While not concerned with meeting a specific absolute error at a particular level of significance, as Law and Kelton described in their book, I focused on ensuring that the absolute error (represented

by standard error) of each mean was less than 0.1 of the mean. [Law and Kelton, 1991]
This was easily achieved through a sample size of 100. I provide the mean value of these runs for each C^2 process in the table below.

Decision Point	Inter arrival time	Information Certainty	Human factor	Number of survival		
				PCW	NCW	CEC
1	1	1	1	0	0.53	10
2	1	1	0	0	0.75	10
3	1	1	-1	0	0.55	10
4	1	0	1	0	0	6
5	1	0	0	0	0	6
6	1	0	-1	0	0	6
7	1	-1	1	0	0	0.24
8	1	-1	0	0	0	0.66
9	1	-1	-1	0	0	0.16
10	0	1	1	0	1.27	10
11	0	1	0	0	2.29	10
12	0	1	-1	0	1.88	10
13	0	0	1	0	0	6
14	0	0	0	0	0.74	6
15	0	0	-1	0	0.38	6
16	0	-1	1	0	0	1.01
17	0	-1	0	0	0	0.97
18	0	-1	-1	0	0	1.07
19	-1	1	1	0	7.39	10
20	-1	1	0	0	7.65	10
21	-1	1	-1	0	7.55	10
22	-1	0	1	0	1.25	6
23	-1	0	0	0	1.02	6
24	-1	0	-1	0	0.81	6
25	-1	-1	1	0	0	2.97
26	-1	-1	0	0	0	3
27	-1	-1	-1	0	0	3

Table 7. Summary of Simulation Output.

A very significant result is that PCW has mean value of '0' at all decision points. This implies that individual ship cannot survive in the scenario portrayed in this simulation environment, as decision time for PCW is too great to overcome. The task forces with CEC survive without the loss of ship when task force consists of 6 or 10 ships, yet the task force has less success when it begins with 3 ships. Nevertheless, CEC is the most capable C^2 system to defend air threat while NCW capability improves with a larger friendly task force.

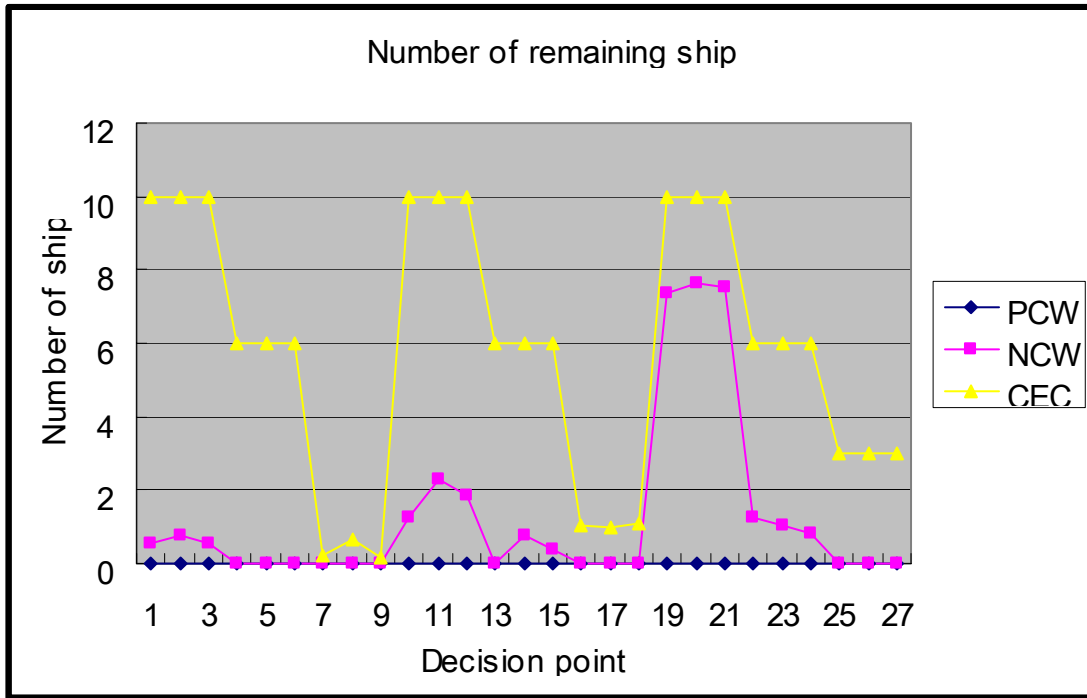


Figure 21. Number of Remaining Ship.

G. STATISTICAL ANALYSIS

The results above show that PCW C^2 process has no effectiveness within the experimental environment in this simulation. I therefore focus the remainder of my statistical analysis on NCW and CEC. I develop a metamodel based on the simulation output for NCW and CEC. A metamodel is an algebraic function relating the response to the important input factors serving as at least a rough proxy for full-blown, simulation and its purpose is to estimate or approximate the response surface. [Law and Kelton, 1991]

In the development of this metamodel, the response variable is changed to survival ratio for statistical analysis instead of number of remaining ships. The survival rate is the ratio of the number of remaining ships after engagement to the initial number in the task force, and this response variable remove the impact of the initial number of ship.

Decision point	NCW	CEC
1	0.053	1
2	0.075	1
3	0.055	1
4	0	1
5	0	1
6	0	1
7	0	0.08
8	0	0.22
9	0	0.0533333
10	0.127	1
11	0.229	1
12	0.188	1
13	0	1
14	0.1233333	1
15	0.0633333	1
16	0	0.3366667
17	0	0.3233333
18	0	0.3566667
19	0.739	1
20	0.765	1
21	0.755	1
22	0.2083333	1
23	0.17	1
24	0.135	1
25	0	1
26	0	1
27	0	1

Table 8. Survival Rate.

1. Metamodel of NCW and CEC

My initial metamodel was a polynomial regression that included the three main effects, their squared terms, and all interactions. The purpose of including all of these

terms is to find the model with the best fit, indicated by highest adjusted R^2 [Devore, 2003] The adjusted R^2 is preferred over R^2 , as it takes into account the contribution of merely the presence of additional model factors. Additionally, I include polynomial terms in order to account for any nonlinearity in the response surface. The initial model output is below.

NCW	Coefficient	Std. Error	T statistics	p-value
Intercept	0.0373	0.0411	0.9071	0.3778
Inter arrival time	-0.1439	0.0190	-7.5584	0.0000
Information certainty	0.1659	0.0190	8.7613	0.0000
Human factor	-0.0038	0.0330	-0.2014	<u>0.8429</u>
Inter arrival time ²	0.0830	0.0330	2.5179	0.0228
Information certainty ²	0.0881	0.0330	2.6729	0.0167
Human factor ²	-0.0223	0.0330	-0.6758	<u>0.5088</u>
Inter arrival time : Information certainty	-0.1730	0.0233	-7.4219	0.0000
Inter arrival time : Human factor	-0.0049	0.0233	-0.2121	<u>0.8347</u>
Information certainty : Human factor	-0.0066	0.0233	-0.2824	<u>0.7812</u>
Inter arrival time : Information certainty : Human factor	0.0017	0.0285	0.0613	<u>0.9519</u>

Table 9. Polynomial Regression Output of NCW Response.

The adjusted R^2 for this model is 0.872947, which explains a significant amount of variation of simulation output. But, the high p-values of the human factors term, all interaction terms with human factor, and the squared human factor term are very high, and therefore, human factor is not statistically significant. I remove these terms, and the result is below.

NCW	coefficient	Std. Error	T statistics	p-value
Intercept	0.0224	0.0309	0.7259	0.4795
Inter arrival time	-0.1439	0.0169	-8.4947	0.0000
Information certainty	0.1639	0.0169	9.7961	0.0000
Inter arrival time ²	0.0830	0.0293	2.8298	0.0100
Information certainty ²	0.0881	0.0293	3.0040	0.0068
Inter arrival time : Information certainty	-0.1730	0.0207	-8.3413	0.0000

Table 10. Polynomial Regression After Removing Non Significant Factor.

The adjusted R^2 for this model is 0.905657 that is an improvement over the initial model, and all remaining terms, based on p-value, are statistically significant.

a. Analysis of NCW

As described by Devore, the adequacy of a regression model depends on meeting the assumptions of normality and constant variance.

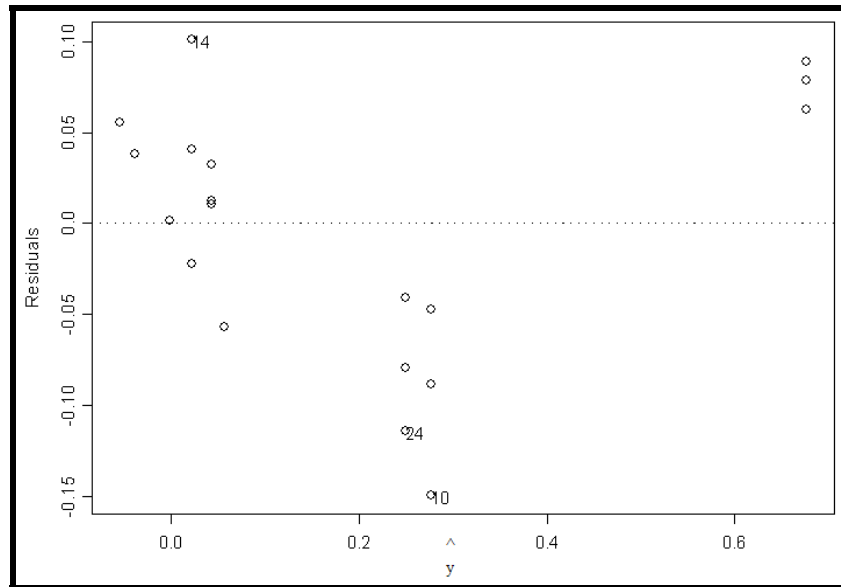


Figure 22. Residual vs. Fitted Value of NCW.

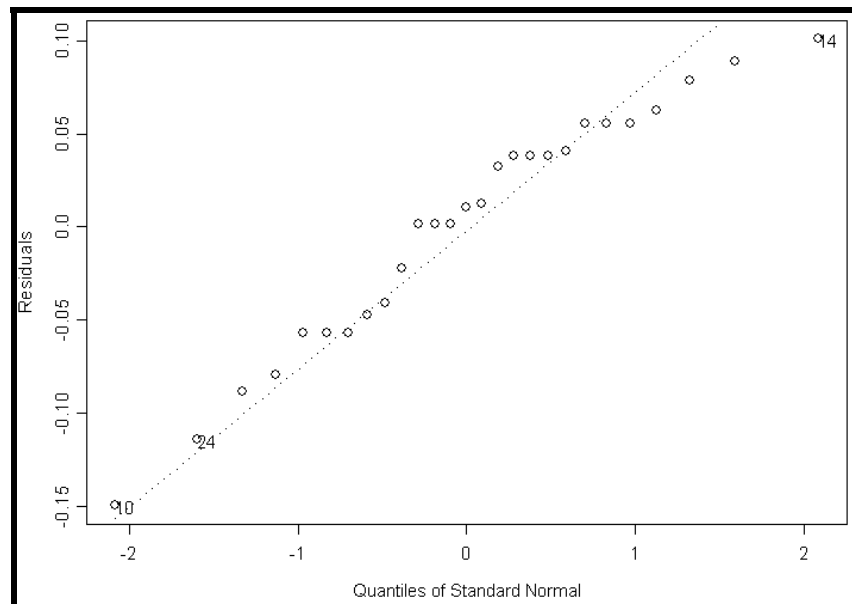


Figure 23. Quantiles of Standard Normal Plot of NCW.

Figure 22 is a plot of residuals versus fitted value $\left(\text{or } \hat{y}\right)$, while Figure 23 is a normal probability plot. While the normality assumption is met, Figure 22 is somewhat troubling in that it shows a pattern in the residual plot. This curvature in the residual plot could mean that the constant variance assumption is violated, or that some key input factor has been omitted. Nevertheless, I consider this polynomial regression equation adequate to represent survival rate in an NCW C^2 process. The final regression equation is

$$NCW = 0.0224 - 0.1439\lambda + 0.1639I + 0.083\lambda^2 + 0.0881I^2 - 0.173(\lambda \times I) \quad (4-1)$$

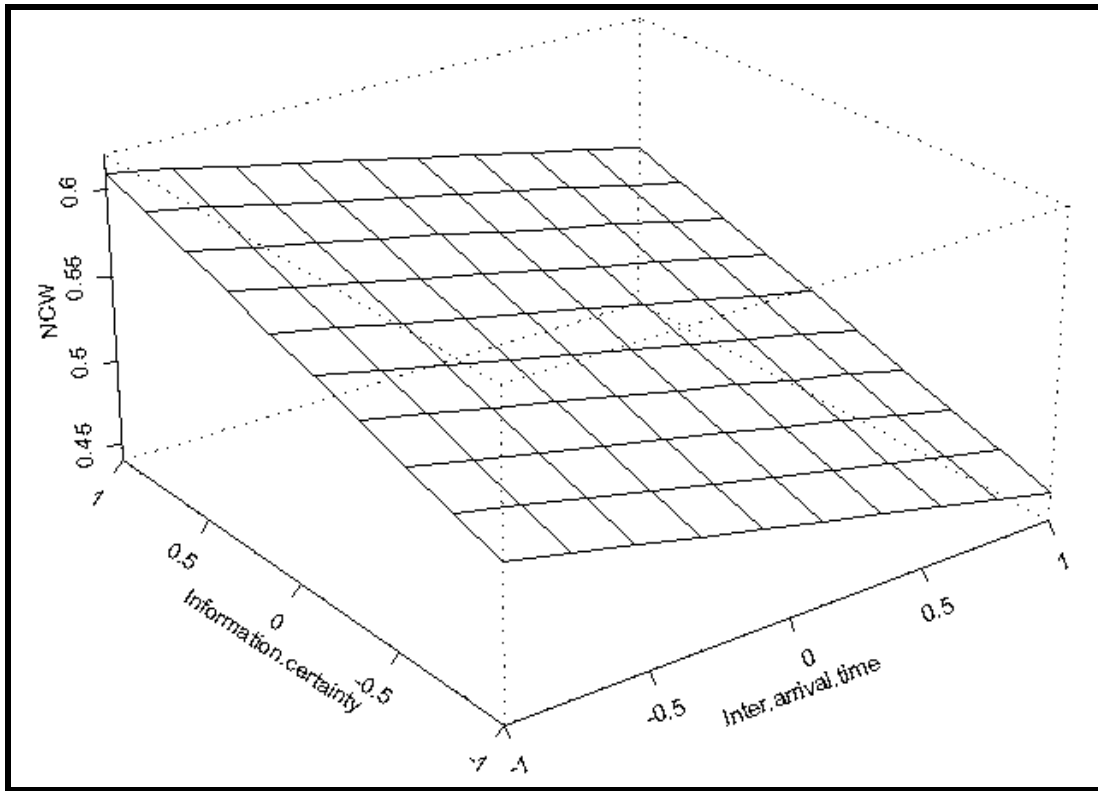


Figure 24. Response Surface of NCW.

Figure 24 shows the response surface based on the NCW metamodel. As coded values of +1 represent high inter arrival time and high information certainty, while -1 represent low inter arrival time and low information certainty, it can be readily discerned from the surface as to the marginal benefit in improving information certainty when faced with a specific arrival rate. Response surface looks flat because the slope of each combined coded value intervals are very slightly different.

b. Analysis of CEC

I analyze CEC with polynomial regression in the same manner as earlier as NCW. However, human factor has no relationship with CEC, as I discussed in Chapter III. The result is seen below.

CEC	coefficient	Std. Error	t statistics	p-value
Intercept	0.9511	0.0493	19.2893	0.0000
Inter arrival time	-0.1470	0.0270	-5.444	0.0000
Information certainty	0.2572	0.0270	9.5243	0.0000
Inter arrival time ²	0.0733	0.0468	1.5677	0.1319
Information certainty ²	-0.2572	0.0468	-5.4988	0.0000
Inter arrival time : Information certainty	0.2206	0.0331	6.6680	0.0000

Table 11. Polynomial Regression of CEC Response.

The regression results for CEC indicate that all terms in this model for each factor, except inter arrival time² are statistically significant. Adjusted R² is 0.87507 and p-value is very small. I check adequacy of this regression equation.

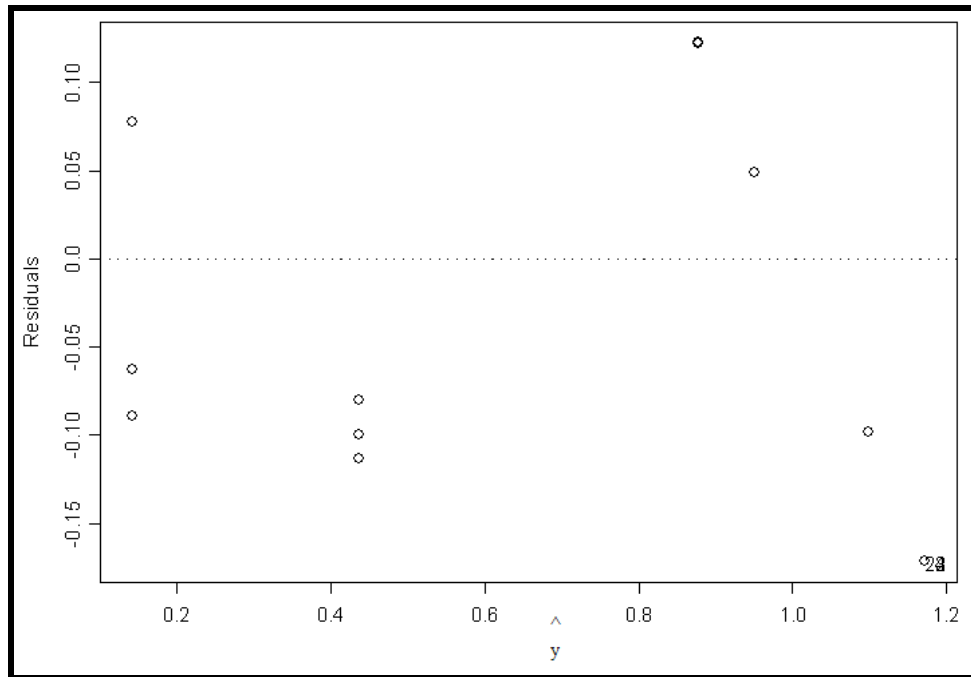


Figure 25. Residual vs. Fitted Value of CEC.

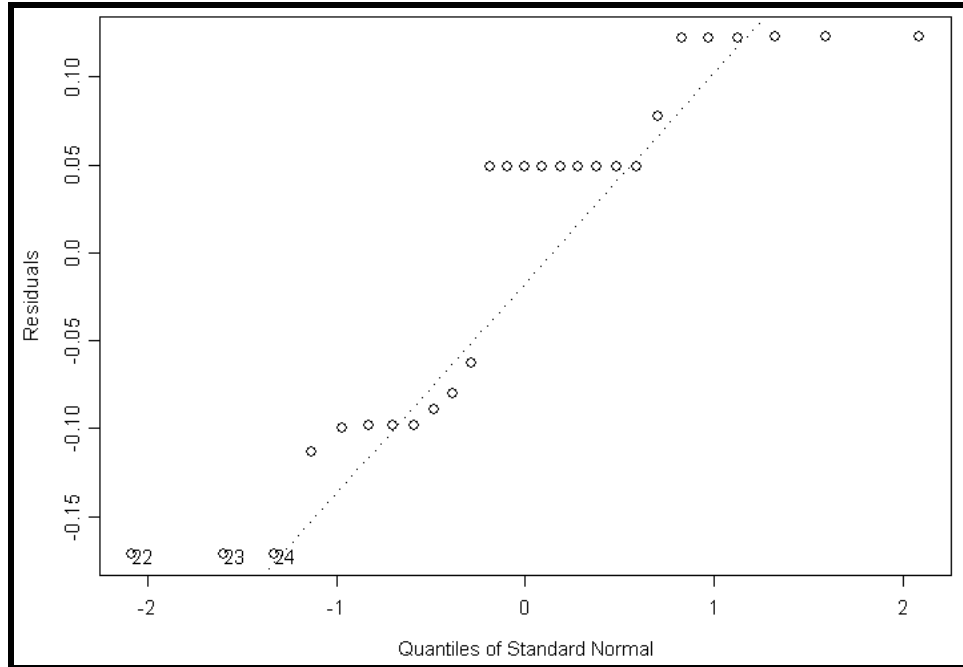


Figure 26. Quantiles of Standard Normal Plot of CEC.

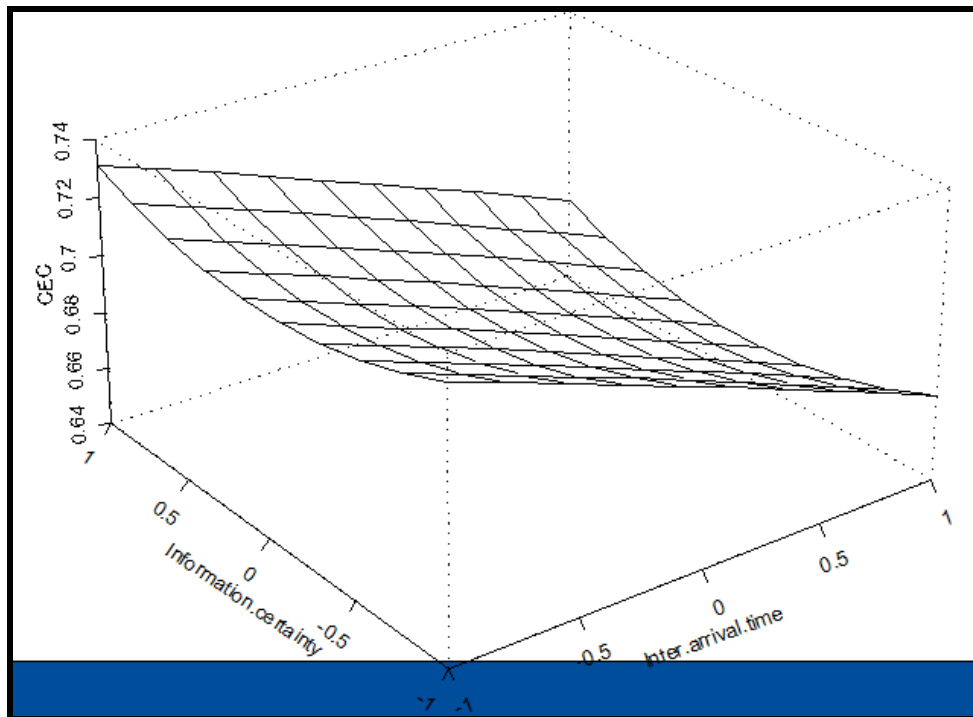


Figure 27. Response Surface of CEC.

The residual plot in Figure 25 shows that CEC regression equation roughly meets constant variance assumption. However, the normality assumption is

possibly violated in Figure 26. Figure 27 shows response surface of CEC, based on regression output. The model curvature is more pronounced. I consider this polynomial regression equation adequate to respect survival rate in CEC process. The final polynomial regression equation is:

$$\begin{aligned} &\text{Ratio of ships remaining} \\ &= 0.9511 - 0.147\lambda + 0.2572I + 0.0733\lambda^2 - 0.2572I^2 + 0.2206(\lambda \times I) \quad (4-2) \end{aligned}$$

2. Estimation of α

The final analytical concern of this study is to estimate α , the probability of survival enhanced by improved C^2 time impact. I estimate α based on simulation output, realizing that the true α is scenario dependent. Therefore, a change of the situation (with input variable changes) affects the simulation output and α . Nevertheless, I use the regression equations, or metamodel, as it can provide overall insight into the true value of α .

I estimate α by forming a ratio of CEC to NCW. The inter arrival time and information certainty are input as coded value and I use marginal value of response surface as survival rate. I calculate α by dividing survival rate of CEC with survival rate of NCW.

$$\alpha_{CEC/NCW} = \frac{0.9511 - 0.147\lambda + 0.2572I + 0.0733\lambda^2 - 0.2572I^2 + 0.2206(\lambda \times I)}{0.0224 - 0.1439\lambda + 0.1639I + 0.083\lambda^2 + 0.0881I^2 - 0.173(\lambda \times I)} \quad (4-4)$$

It is apparent that α will vary over the range of values for information certainty and inter arrival rate. Therefore, I create a response surface for α by dividing each variable into 10 sub intervals. This results in 100 surface survival rate points of both NCW and CEC. I calculate the mean and variance of α over this region.

Alpha	
Minimum value	1.199
Maximum value	1.466
Mean value	1.299
Variance	0.00476
Standard deviation	0.0689

Table 12. Statistical Value of α .

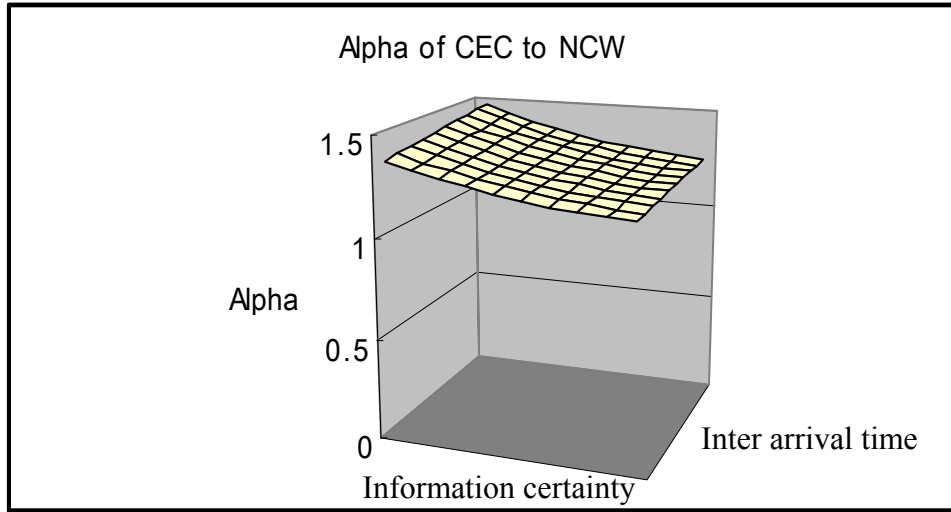


Figure 28. α of CEC.

Table 12 a statistical summary of α , while Figure 28 shows the surface of α with 100 data, the expected value is 1.299 and its variance is 0.00476. As the variance is small in relation to the mean, I can confidently conclude that CEC system can improve probability of survival at a rate of 1.299 relative to NCW.

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V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

It is apparent that enhanced C^2 system can have improved engagement outcomes. NCW and CEC can elevate engagement capability by improving information superiority. I estimated its improvement by enhancing the MOE of C^2 systems of NCW and CEC. NCW and CEC can apply to any phase of warfare. However, I focus on anti missile defense because CEC is mainly developed for littoral anti air defense.

I use Schutzer's C^2 theory as a foundation for this research. He developed a model for naval engagement and his significant contribution is that he predicted the significance of time regarding enhanced C^2 system. My analysis focuses on this time impact to the commander's decision time. I modified Schutzer's theory and estimate MOE and coefficient α of the probability of survival with mathematical and simulation method.

In estimating the C^2 MOE mathematically, I defined three parameters (decision time, information certainty, and human factor) and estimate their values and I calculate three factors (probability of survival, allocation ratio, and exchange rate). Information certainty and human factor are my contributions to C^2 analysis. Information certainty of NCW and CEC is affected directly by the number of ships, but under PCW, information certainty stays constant. This implies the contribution of the network complexity to C^2 system. The human factor implies commander's personal character. I assume that NCW is affected by both of these parameters, but that CEC is not affected by human factor.

I calculate the decision time for each C^2 operating process and implement into MOE equation. The result shows that CEC can improve the friendly force chance for success relative to NCW and PCW. Superior information certainty greatly affects the MOE.

I estimate the enhanced coefficient α of the probability of survival based on a simulation model. I simulate an air defense scenario and use the input I derived explaining decision time, information certainty, and human factor as simulation parameters. In addition, I introduce missile inter arrival time into simulation. My simulation output indicates that PCW cannot be compared with NCW or CEC, in that

PCW has no survivability within simulation environment. In order to estimate α and compare NCW and CEC, I develop a metamodel through polynomial regression based on simulation outputs. This metamodel show NCW and CEC are not affected by human factor but are affected by missile inter arrival time and information certainty. Both metamodels provide prediction capability by mapping a response surface.

Based on the regression equations, I obtain 100 response surface points for each NCW and CEC, and calculate α with these data points. With a simple statistical calculation, I estimate mean value and variance of α of CEC to NCW. The mean value is 1.299 and variance is 0.00476, as the variance very small in relation to mean, I conclude with confidence that CEC can improve MOE by 1.299 relative to NCW.

As a result, I find the NCW or CEC can improve capability of C^2 system, with CEC providing the greatest improvement. Statistical analysis shows that NCW and CEC are not affected by human factor. Enhancement of C^2 system results from the information certainty that is caused by network reinforcement. Finally, this research supports the CEC methodology and its contribution to engagement capability.

B. RECOMMENDATIONS

There are three areas concerning this research that deserve further study. The first concerns the other parameters in Schutzer's specific C^2 theory that I did not consider. These are initial information accuracy (σ^2) and density of enemy distribution. These two factors could possibly have a significant effect on C^2 .

Second, there are other important features of CEC that may influence the result of both mathematical and simulation output. Two of these are precision cueing and composite tracking. Accurately representing these two variables may allow for representing the contribution of CEC to operational success.

Finally, it could be interesting to develop a more fidelity in more detailed simulation. As I mentioned above, combat engagement results in interaction, and the air defense situation will be changed as friendly force counterattack. The enemy force firing missile policy will also change. Other aspects that can influence the result are missile inter arrival time distribution, detection probability, type of ship, kinds of anti air missile, and so forth. In other words, there are parameters that were considered and some that

vary throughout the engagement. Introducing these parameters, and updating them realistically throughout the engagement can help estimate more exactly the MOE and coefficients.

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